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The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART B

RADIO AND ELECTRONIC ENGINEERING
(INCLUDING COMMUNICATION ENGINEERING)

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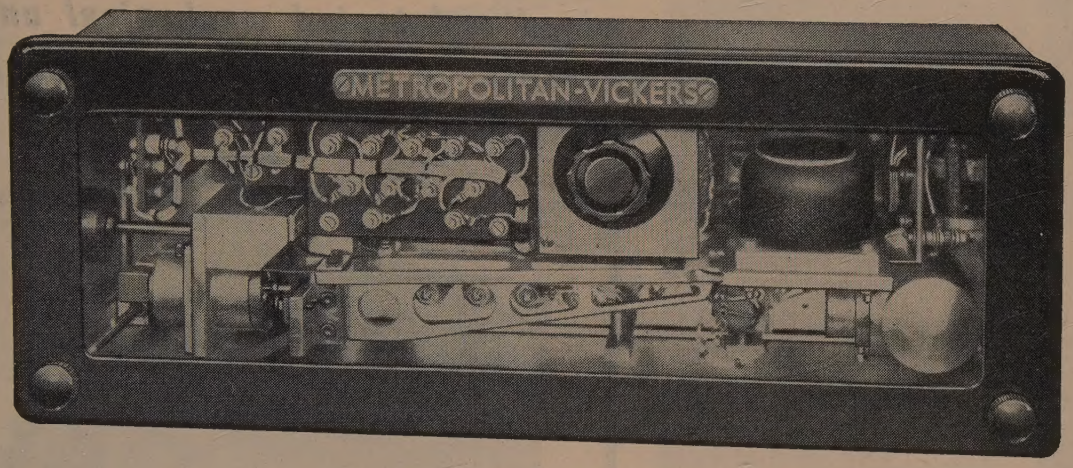
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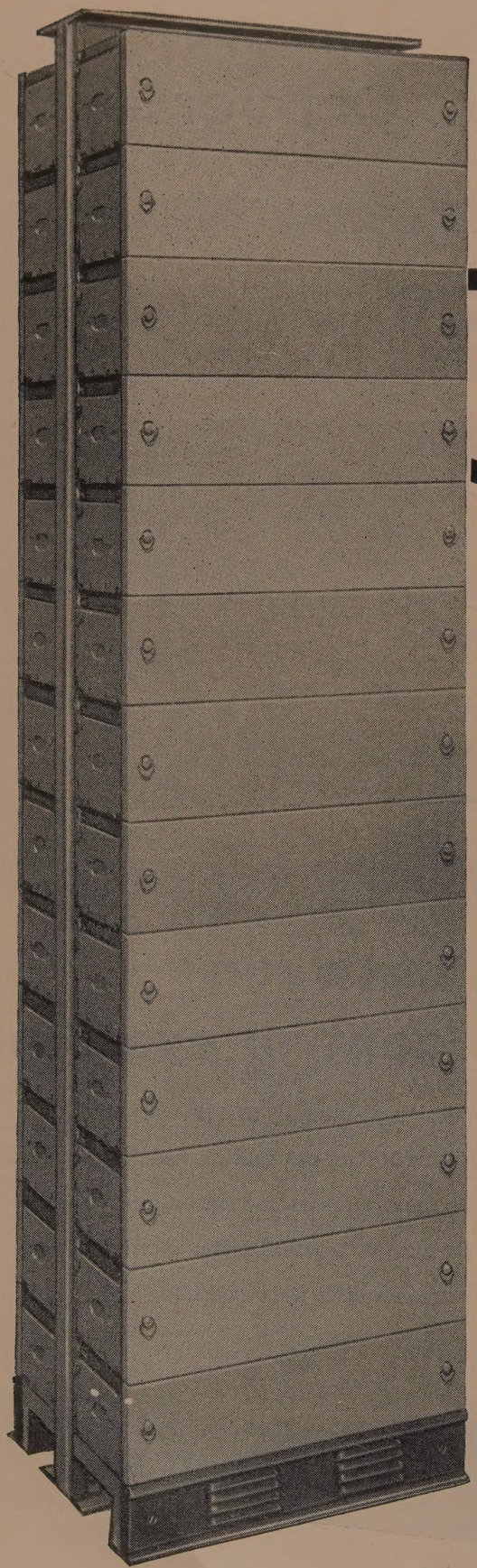
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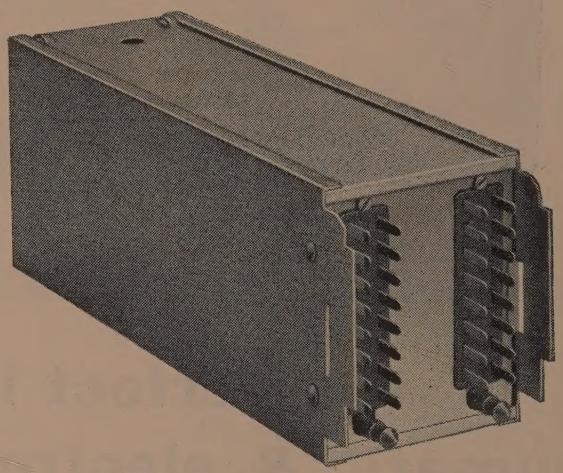
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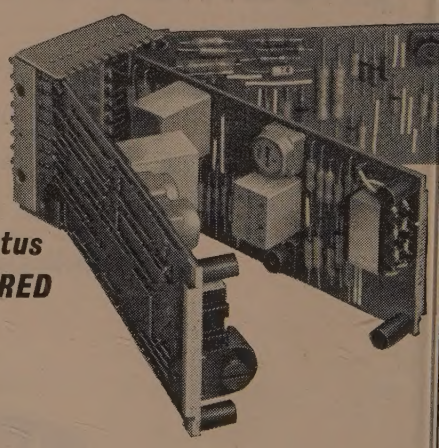
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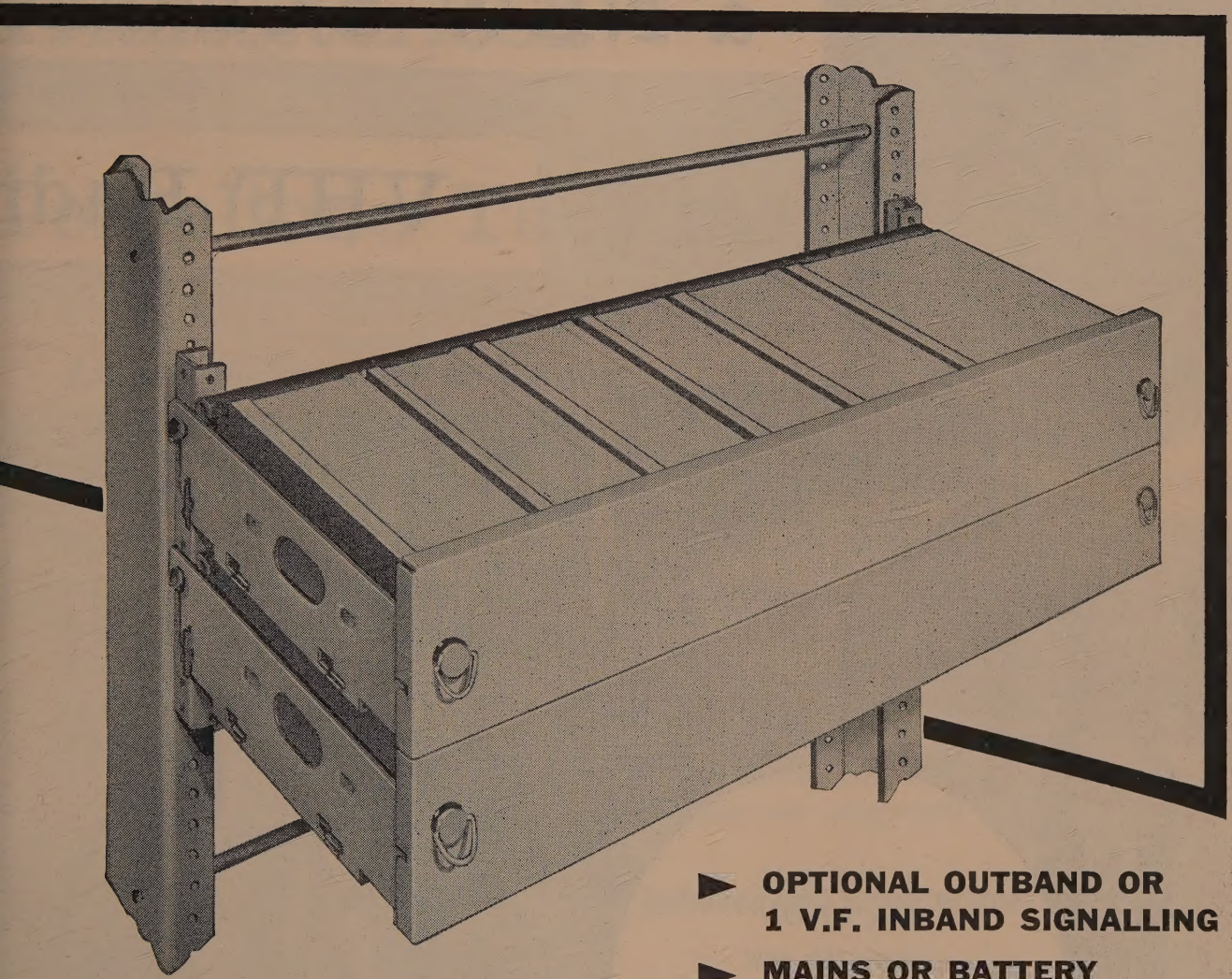
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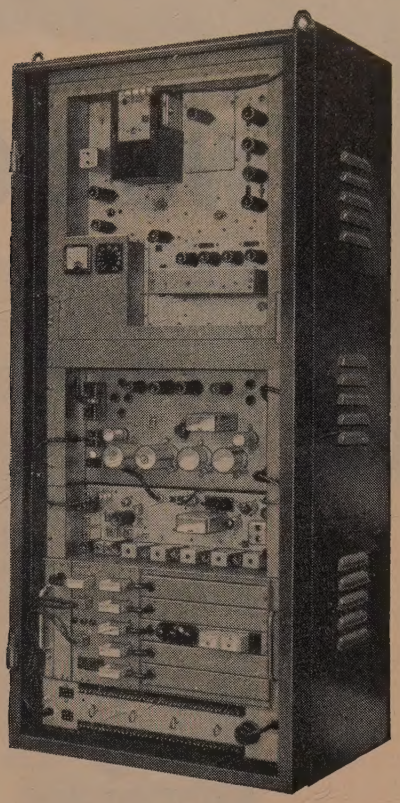
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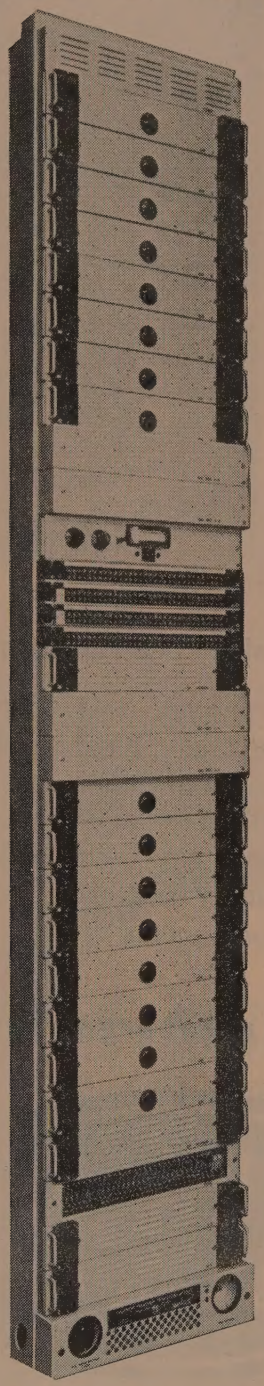
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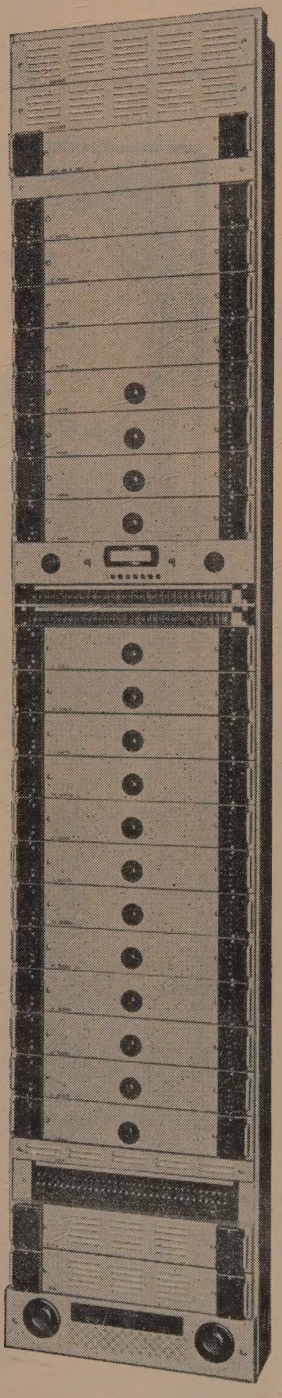
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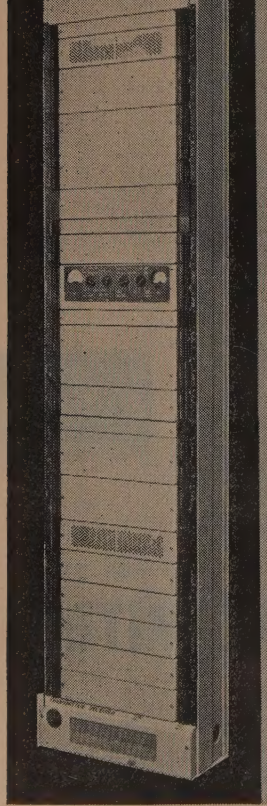
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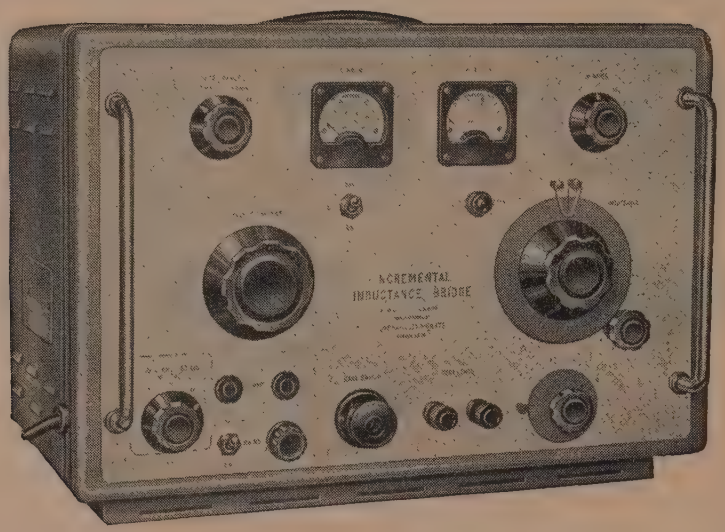
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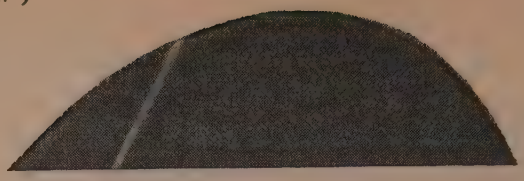
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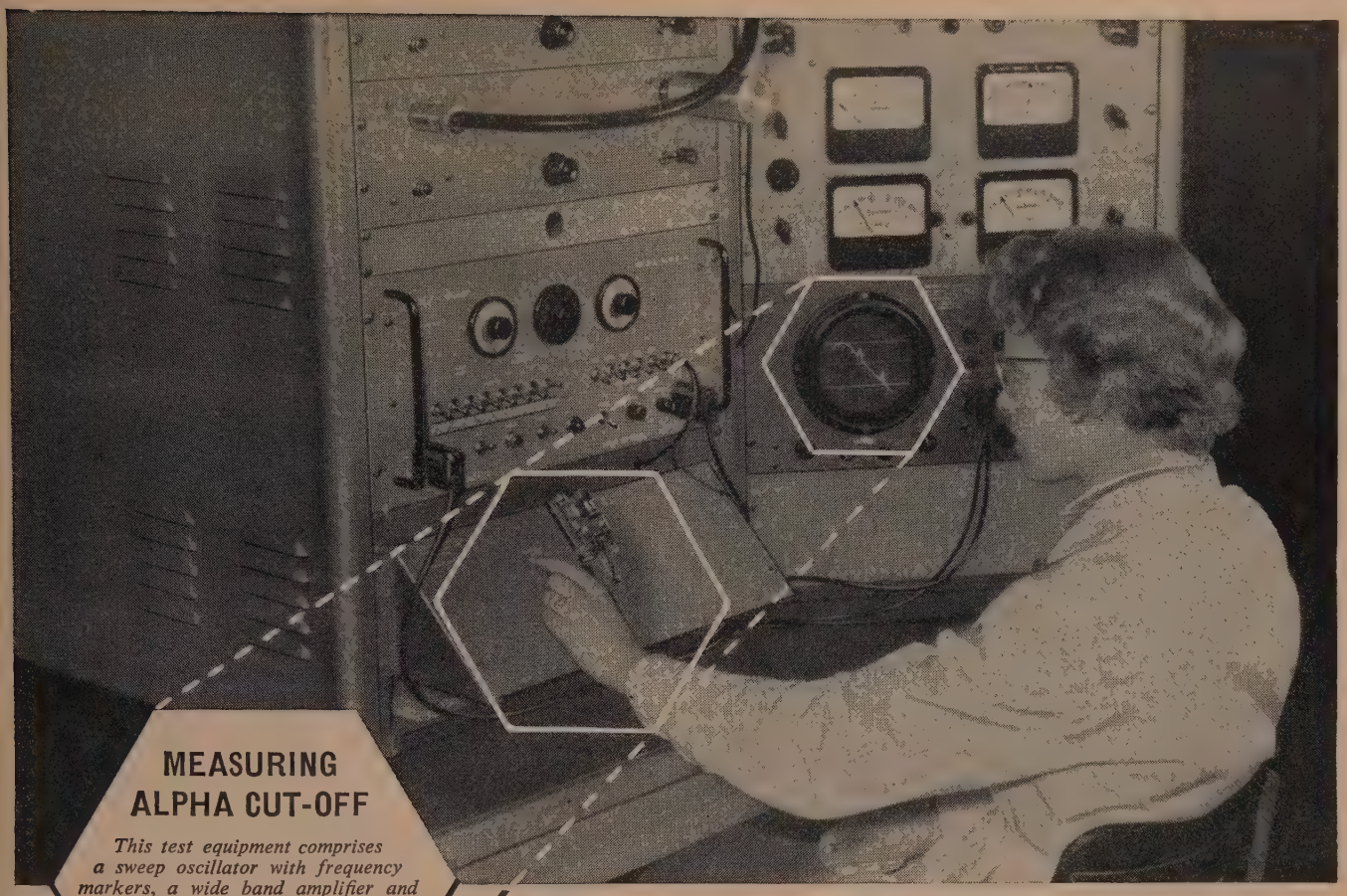


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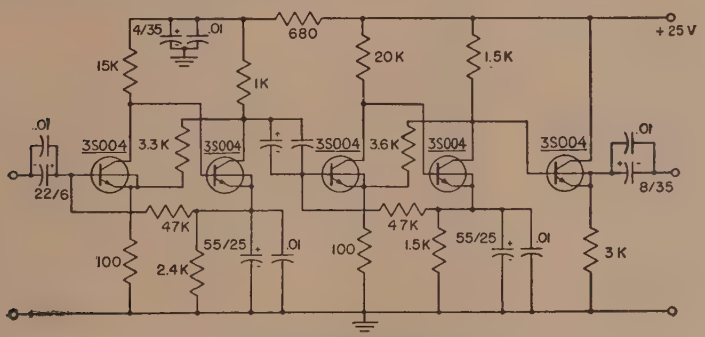
MAXIMUM RATINGS

Collector dissipation at 25°C.	125 mW
Collector dissipation at 100°C.	50 mW
Collector Breakdown voltage	30 volts
Collector current	10 mA

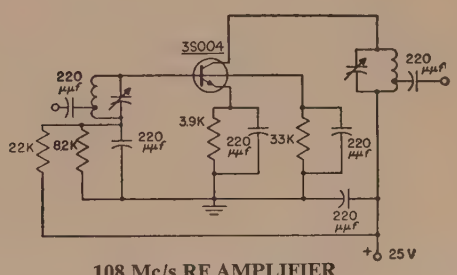
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Type No.	*Power Gain*
3S002 (3N34)	16 db (min) at 30 Mc/s.
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10 Mc/s VIDEO AMPLIFIER
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BACKGROUND On 1st December, 1958, the G.P.O.'s new Subscriber Trunk Dialling (S.T.D.) scheme comes into operation on the Bristol Central Exchange, by 1970 it will embrace three quarters of all trunk calls in the United Kingdom.

When S.T.D. is introduced, *all* telephone calls, whether trunk or local, can be dialled. The calls will be charged in twopenny units. *It is these units that SMITHS Subscriber's Private Meter has been designed to indicate.*

THE INSTRUMENT This consists essentially of a meter, designed to British G.P.O. specification, housed in a shock resisting plastic case. The meter dial has two scales marked 0-100 units. The outer scale in yellow registers units, the inner white scale registers hundreds. A yellow and white pointer are associated with the two scales.

A third pointer in red also registers units but can be reset to zero by depressing the red button in order to register the cost of an individual call. Operation of the reset button does not interrupt the function of the meter and the yellow and white pointers will continue to summate the call charges.

SALIENT FEATURES No audible noise interference.

Does not respond to voltages less than 100V. 25 c/s A.C. under normal ringing conditions or fault conditions.

This meter will be available to subscribers on the S.T.D. system in the U.K. by rental from the G.P.O.

Overseas enquiries should be made direct to the address below.

SMITHS

are proud to be associated with S.T.D.

SMITHS

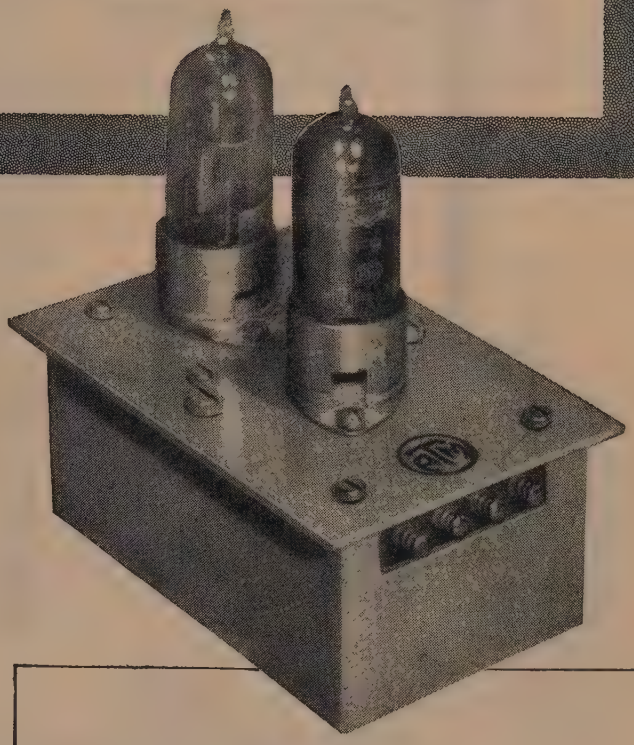
INDUSTRIAL INSTRUMENT DIVISION

Chronos Works, North Circular Road, London, N.W.2.

Telephone: GLAdstone 1136

Introducing a new

CRYSTAL OSCILLATOR - THERMALLY COMPENSATED



- **Superior frequency/temperature coefficient of the order of .05/10^6/°C over wide temperature ranges.**
- **No contacts, thermostats or mechanical parts.**
- **Immediately ready for use on switching on, no crystal heater required.**
- **Improved ageing characteristics.**
- **Particularly suitable for mobile applications.**

This crystal oscillator has been designed by A.T.E. to overcome the disadvantages of oscillators of the oven mounting type in situations where immediate operational availability is called for, i.e. transport and defence requirements. The unit has the advantages also of great compactness, very simple design and static components.

TYPICAL CHARACTERISTICS :—

Frequencies available: 4 Mc/s to 16 Mc/s

Temperature range: Either — 20°C to + 70°C
or 0°C to + 50°C

Max. frequency excursions over temperature ranges:
Either ± 5 parts per million
or ± 10 parts per million
} as required.

Output: 1 to 5 volts (according to frequency, etc.) into a load consisting of 100,000 ohms in parallel with 10 pF, simulating a following amplifier.

Power Supplies: HT 230 volts 8mA approx.
LT 6.3 volts 0.3 amps.

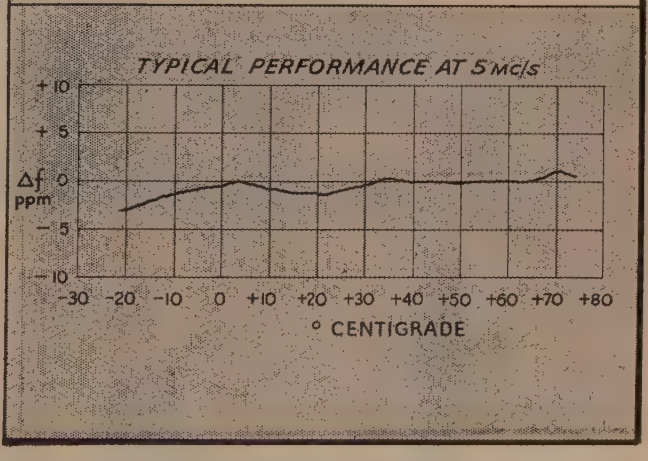
Crystals: Style E (B7G) Special Assembly.

Valve: EF91.

Finish: Grey enamel, on silver-plated copper.

Alternative designs—mains or battery operated—are available and other characteristics can be catered for to customers requirements.





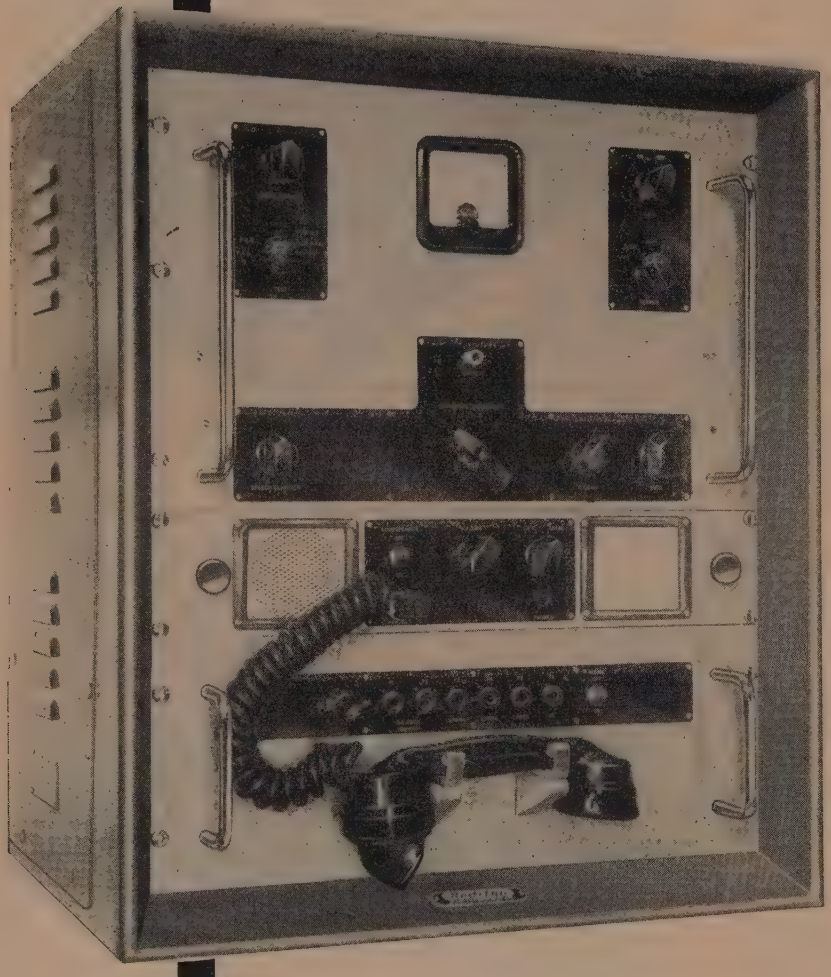
AUTOMATIC TELEPHONE & ELECTRIC CO. LTD.
STROWGER HOUSE, ARUNDEL STREET, LONDON, W.C.2
Telephone: TEMple Bar 9262. STROWGER WORKS, LIVERPOOL 7

AT14841

Redifon

THE WORLD'S LEADING MANUFACTURERS OF RADIOTELEPHONES

introduce the GR.400 TRANSISTORISED SSB Radiotelephone



TRANSISTORISED — for reliability, compactness, minimum weight and power consumption.

THIRD METHOD of SSB eliminates the need for expensive filters and critical adjustment.

SIMPLEX or DUPLEX — the standard model is for Simplex — an additional receiver is supplied for Duplex operation.

COMPATIBLE — for use on single sideband or in conventional double sideband networks.

COMPACT — only 14 ins. deep, for conveniently mounting on desk or table top.

CLIMATIC SPECIFICATION — continuous rating −20°c to + 55°c

Brief Tech. Specification

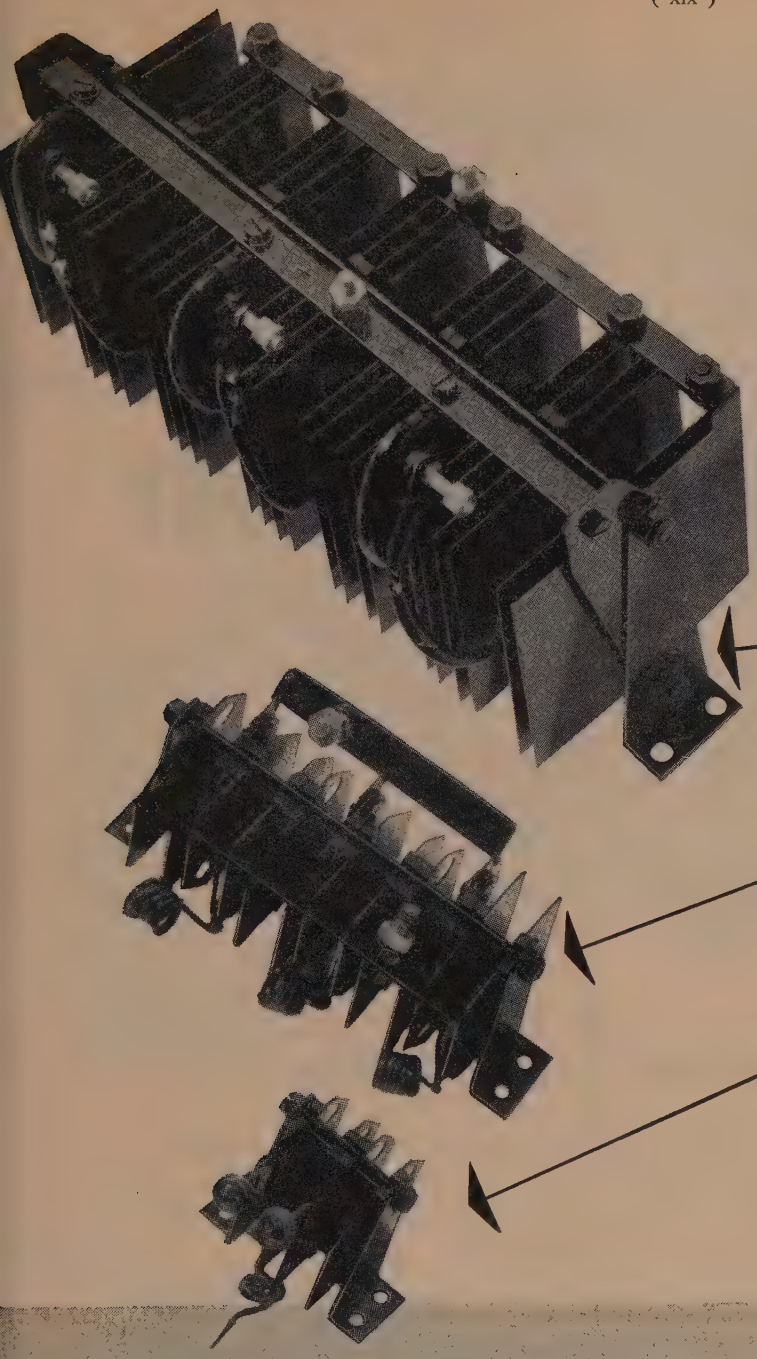
Power output : 60 watts P.E.P.
Frequency range : 2 - 10 Mc/s.
Channels : 4 crystal controlled spots in any part of the range.
Dimensions : 25″ x 21½″ x 14″ deep.
Power supplies : 100-125v or 200-250v AC or transistorised 12 or 24v DC.
Power consumption : 280 VA for 60 watt output.

for R/T or CW operation

With all the advantages of single sideband, giving an effective power output of 500 watts double sideband, the GR.400 is still as simple to operate as an ordinary telephone. The first transistorised radiotelephone, this new model further enhances the wide range of Redifon radiotelephones—many thousands of which are in use all over the world.

No. 68 AR

REDIFON LIMITED Radio Communications Division, Broomhill Road, London S.W.18
Telephone: Vandyke 7281 *A Manufacturing Company in the Rediffusion Group*



HIGH POWER SILICON RECTIFIER STACKS

Ratings up to 150 amps. Size 12″ x 5″ x 4½″ (incl. mounting brackets).

Ratings up to 40 amps. Size 6⅛″ x 3″ x 2⅞″ (incl. mounting brackets).

Ratings up to 16 amps. Size 2¾″ x 2½″ x 2″ (incl. mounting brackets).

FERRANTI

APPLICATIONS

Ferranti high power silicon rectifiers have many applications in the aircraft, electronic, electrical, chemical, marine and general engineering industries including aircraft and marine power supplies, radar systems, computers, chemical processing, welding and electroplating.

SPECIAL FEATURES

- *Reliability at high temperatures.*
- *High power to space ratio.*
- *Very high rectification efficiency.*

FERRANTI LTD GEM MILL · CHADDERTON · OLDHAM · LANCASHIRE

Telephone: MAIn 6661

London Office: KERN HOUSE, 36, KINGSWAY, LONDON W.C.2. *Tel:* TEMple Bar 6666

FE 186/2



A.T.E + MARCONI

Combined Operations

The complexity of modern radio-multichannel systems involving hundreds of telephone channels has brought about a collaboration between the two leading specialist organizations in the field—Marconi's in radio, and A.T.E. in carrier transmission.

This completely unified approach to development, systems planning, supply, installation, maintenance of equipment and training of personnel covers radio-multichannel systems in the V.H.F., U.H.F. and S.H.F. frequency bands all over the world.

Full information may be obtained from either:
MARCONI'S WIRELESS TELEGRAPH COMPANY LIMITED, CHELMSFORD, ESSEX, ENGLAND.

or AUTOMATIC TELEPHONE & ELECTRIC CO. LTD., STROWGER HOUSE, ARUNDEL STREET, LONDON, W.C.2

Audio Power Valves





for
Relay Services
Public Address Systems
Vibration Equipment

Mullard audio power valves are available both for new equipment designs and maintenance. Full data for these power valves and details of xenon and mercury vapour rectifiers for associated power supplies are readily obtainable from the address below.

AUDIO POWER AMPLIFIER VALVES

	Type No.	pa max. (watts)	Va max. (kilovolts)	Ik max. (amps)	Power Output (2 valves) (kW)
For Maintenance	*Triodes*				
	MZ2–200	275	2.4	0.4	1.2
	MY3–275	275	3.0	0.5	1.3
For New Equipment	TY2–125	135	2.5	0.25	0.7
	TY3–250	250	3.0	0.48	1.3
	TY4–500	450	4.0	0.7	2.4
	TY7–6000A	6000	7.2	2.8	20
	Tetrodes				
	QY3–65	65	3.0	0.22	0.27
	QY3–125	125	3.0	0.32	0.55
	QY4–250	250	4.0	0.45	1.2

POWER RECTIFIER VALVES

	Type No.	PIV max. (kilovolts)	Max d.c. output current (amps)	Typical heating up time (secs)
Mercury Vapour	RG1–240A	6.5	0.25	60
	RG3–250A/866A	10	0.25	60
	RG3–1250	13	1.25	60
Xenon	RR3–250/ 3B28	10	0.25	10
	RR3–1250/ 4B32	10	1.25	30

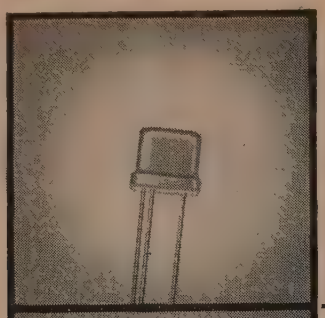
Mullard

GOVERNMENT AND INDUSTRIAL VALVE DIVISION

Mullard

Mullard Limited · Mullard House
Torrington Place · London · WC1 · Tel: LANgham 6633

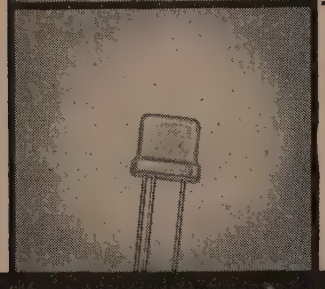
MVT 357b



RF TYPES

		Min. fα
6 Volts	V6/R8	8 Mcs.
	V6/R4	4 Mcs.
	V6/R2	2 Mcs.

Excellent general purpose R.F. transistors which are finding increasing uses in switching circuits. Have useful current gains at high pulse currents and can be selected for 15 and 30 Volt operation. Maximum dissipation now 75 mW; 125 mW on a heat sink. Clips supplied free.



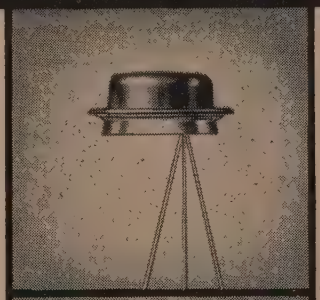
AUDIO TYPES

		Min. Beta
10 Volts	V10/50B	50
	V10/30A	30
	V10/15A	15

An ideal transistor for audio stages of portable receivers. Maximum dissipation now 125 mW; on a heat sink 200 mW. Clips supplied free. Selected types for 30 Volt operation can be supplied to order.

Newmarket GOLTOP* Transistors

NOW 4 RANGES IN PRODUCTION

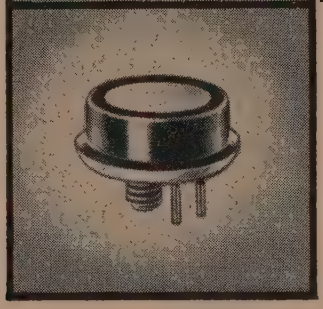


ALL TRANSISTORS ACTUAL SIZE

INTERMEDIATE POWER

Volts		
15	V15/20IP	Min. Beta 20
30	V30/20IP	

With maximum power dissipation of 2 watts, this transistor fills the gap between the audio types and the 10 watt power types in both power output and frequency range. Excellent for low-power transmitters at frequencies up to 500 kc/s. Sealed by cold welding and supplied with special clip mounting, eliminating large fixing studs. 60-Volt types can be selected to order.



POWER

	Minimum Beta		
Volts	10	20	30
15	V15/10P	V15/20P	V15/30P
30	V30/10P	V30/20P	V30/30P
60	V60/10P	V60/20P	V60/30P

The widest range of power transistors available with the closest tolerances. Extremely robust, reliable and stable. High heat dissipation—up to 20 watts per pair used in Class B with suitable heat sink. Up to 80 watts per pair obtainable in Inverter applications. Matched pairs can be supplied.

Leading the way With four years manufacturing experience behind us we are still expanding our production, still increasing our efficiency by new techniques in mechanisation. This policy ensures that the latest developments in transistors will always be offered by Newmarket at extremely competitive prices. The special requirements of every customer receive individual attention.

* *Identified by the gold top.*

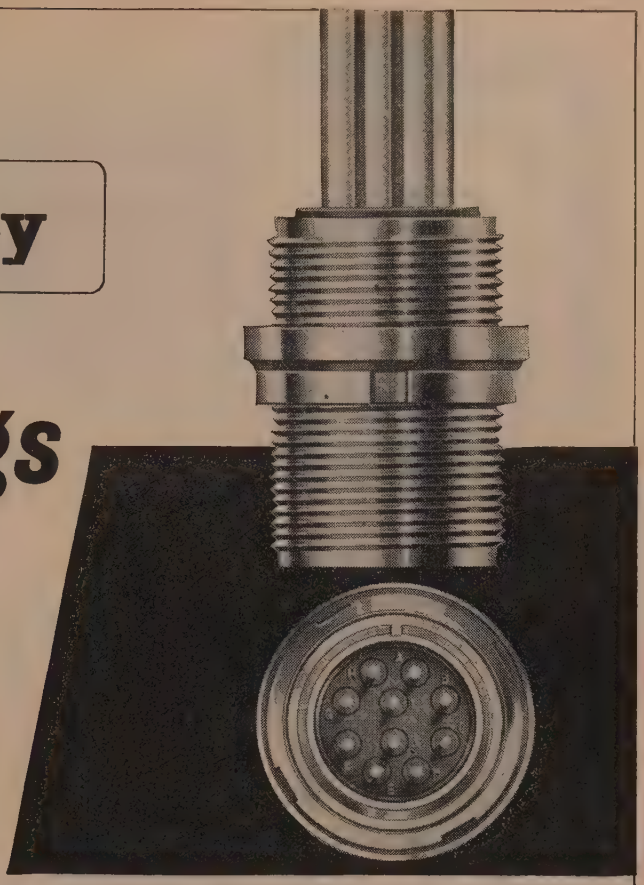
NEWMARKET TRANSISTORS

All enquiries to:

Newmarket
Transistor Co Ltd

Exning Road, Newmarket, Suffolk
Telephone: Newmarket 3381-4 Cables: Semicon Newmarket

A new Plessey range of Plugs and Sockets

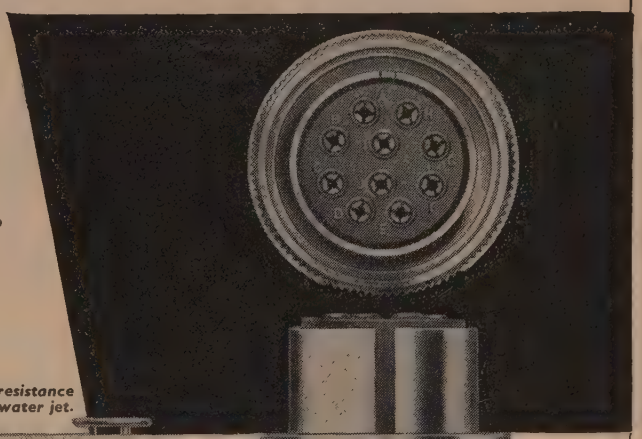


COVERING THE ENTIRE 'AN' RANGE

The Plessey UK–AN series of electrical connectors is now available and, for the first time from a non-dollar source, manufacturers will be able to obtain a full range of plugs and sockets completely interchangeable with the existing AN range.*

The Plessey UK–AN range has been designed and developed to M.O.S. Specification EL 1884 and RCS 321, and UK–AN connectors are fireproof, pressure sealed and environmental resisting. No separate wiring accessories are needed.

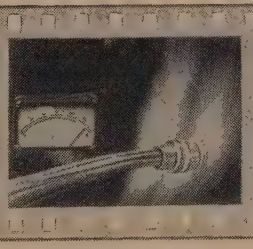
Write for test reports and full technical details.



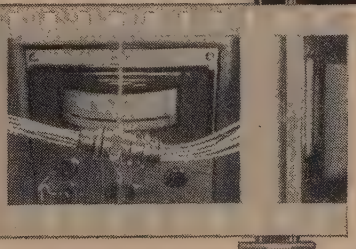
Thawing out after low-temperature test at –60° C.

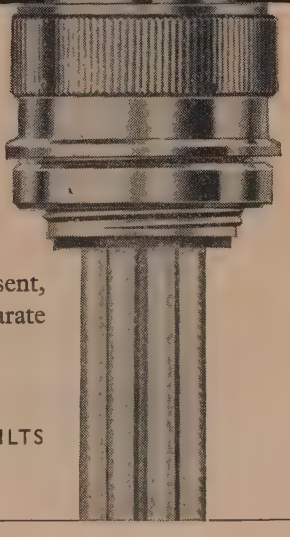


Fireproofness test (15 mins. at 1,100° C.)



Testing insulation resistance under direct water jet.





* There are many thousands of separate items in the AN range as it exists at present, whereas the ingenious Plessey UK–AN list comprises less than a thousand separate items, yet achieves the same service requirements.

ELECTRICAL CONNECTORS DIVISION

THE PLESSEY COMPANY LIMITED · CHENEY MANOR · SWINDON · WILTS

Overseas Sales Organisation: PLESSEY INTERNATIONAL LIMITED · ILFORD · ESSEX

PW2a

Permanent Magnets

Design Advisory Service

No. 10

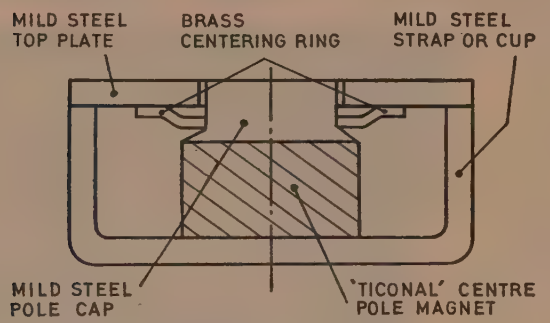
Moving Coil Applications –1

Advertisements in this series deal with general design considerations. If you require more specific information on the use of permanent magnets, please send your enquiry to the address below, mentioning the Design Advisory Service.

The use of modern permanent magnets has resulted in the efficiency of the magnetic systems for moving coil applications being substantially increased during recent years.

The magnet system employed for domestic loudspeakers, which is one of the best known moving coil applications, can be divided into two general types—'centre pole' and 'ring' designs.

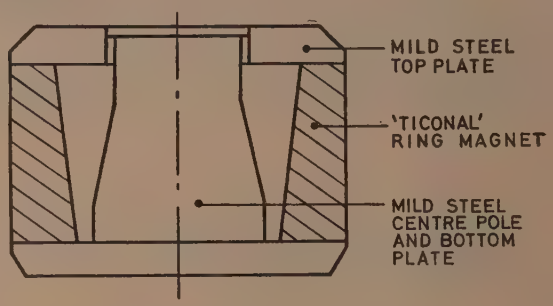
The centre pole design uses a small cylindrical magnet which forms the central pillar of the assembly and is surrounded by a mild steel strap or cup as illustrated. In this design, performance is limited by the size of the magnet which can be arranged within the assembly. If the diameter of the magnet necessitates a collector cap much larger than the one illustrated, the resultant excessive magnetic fringing or leakage will substantially reduce the efficiency of the assembly.



Section of a Typical Centre Pole Moving Coil Strap or Cup Type Assembly. Approximately ½ scale.

An example of the economical use of 'Ticonal' G, the foremost commercial magnet alloy available, is that a magnet with a diameter of 1.14″ and height .765″, weighing only 3.16 oz., will give a total gap flux of 31,200 maxwells. This is equivalent to an average flux density in a .033″ radial air gap of 10,500 gauss, with a mild steel pole diameter of .75″ and a top-plate thickness of .187″. This represents a magnetic efficiency of 50%.

When higher flux densities in the range of 12,000–17,000 gauss are required, the ring type of assembly is utilised. This type of assembly, which is illustrated, can seldom be designed with an efficiency higher than 30% and is, therefore, not normally used in the design of loudspeakers, where cost is an important factor.



Section of a Typical High Performance Ring Type Moving Coil Assembly. Approximately ¼ scale.

For High Fidelity loudspeakers, where the performance is the most important consideration, and when flux densities in the region of 20,000 gauss are required, the ring type of construction is the only possible solution. However, the following table of leakage factors indicates how rapidly leakage losses increase with increasing gap flux density.

1″	diameter	speech	coil	·045″	gap	up to	12,000 gauss x 3
1″	,,	,,	,,	·045″	,,	,,	,, 16,000 gauss x 6
1½″	,,	,,	,,	·050″	,,	,,	,, 16,000 gauss x 6
2″	,,	,,	,,	·050″	,,	,,	,, 20,000 gauss x 8

Whilst the designs mentioned above are referred to as loudspeaker systems, they are also applicable to many other applications using the dynamic moving coil principle, such as vibrators, punch card pulse actuators, public address pressure units, moving coil microphones, etc.

If you wish to receive reprints of this advertisement and others in this series write to the address below.

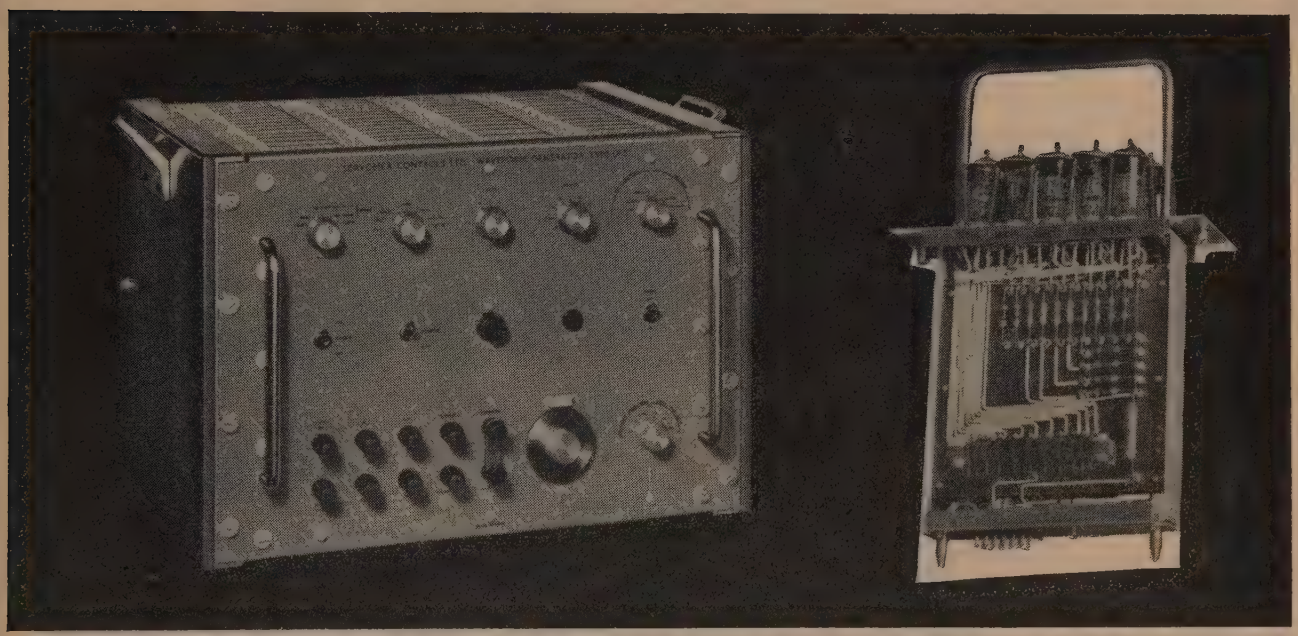
Mullard

'TICONAL' PERMANENT MAGNETS
'MAGNADUR' CERAMIC MAGNETS
FERROXCUBE MAGNETIC CORES

MULLARD LIMITED, COMPONENT DIVISION, MULLARD HOUSE, TORRINGTON PLACE, W.C.1. LANgham 6633
MC271

Unchallenged

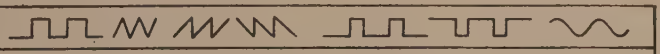
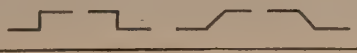
SERVOMEX LF.51 Still the world's best low frequency waveform generator!



Still the most flexible supply of test signals for testing servo mechanisms and automatic controllers

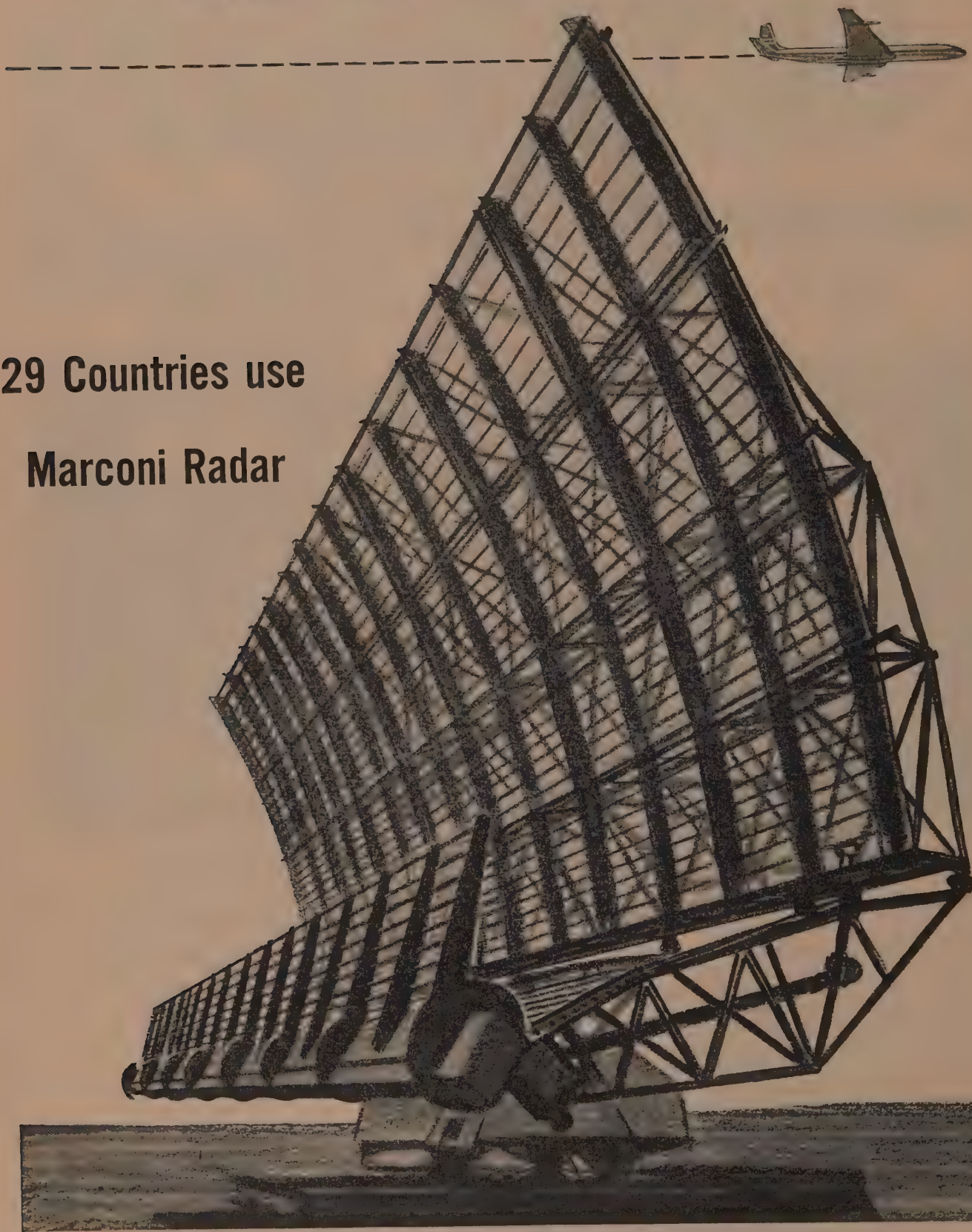
This unique instrument is being used by discriminating control engineers all over the world for measuring the dynamic response of automatic control systems.
With it, one can carry out measurements of the frequency response to sinusoidal input; the step-function response; the response to ramp functions; the response to sine-squared pulses; and many other special tests.

- ★ *Sine waves from 500 cycles/sec. down to one cycle every 2,000 secs. (33 minutes)*
- ★ *Pulses and square waves with rise time of 5 microseconds*
- ★ *Ramp functions with a linear rise variable from 1 millisecond to 1,000 seconds*
- ★ *Over 30 different waveforms available*
- ★ *Voltage variable between 100 microvolts and 150 volts peak-peak*
- ★ *Load current up to 5 milliamps peak*

1. Selector switch at "CONTINUOUS"	
2. Selector switch at "SINGLE" - a step with continuously variable slope.	
3. Selector switch at "DOUBLE" - a single isolated pulse in TEN different forms	

SERVOMEX CONTROLS LIMITED, CROWBOROUGH SUSSEX. CROWBOROUGH 1247

Marconi in Radar



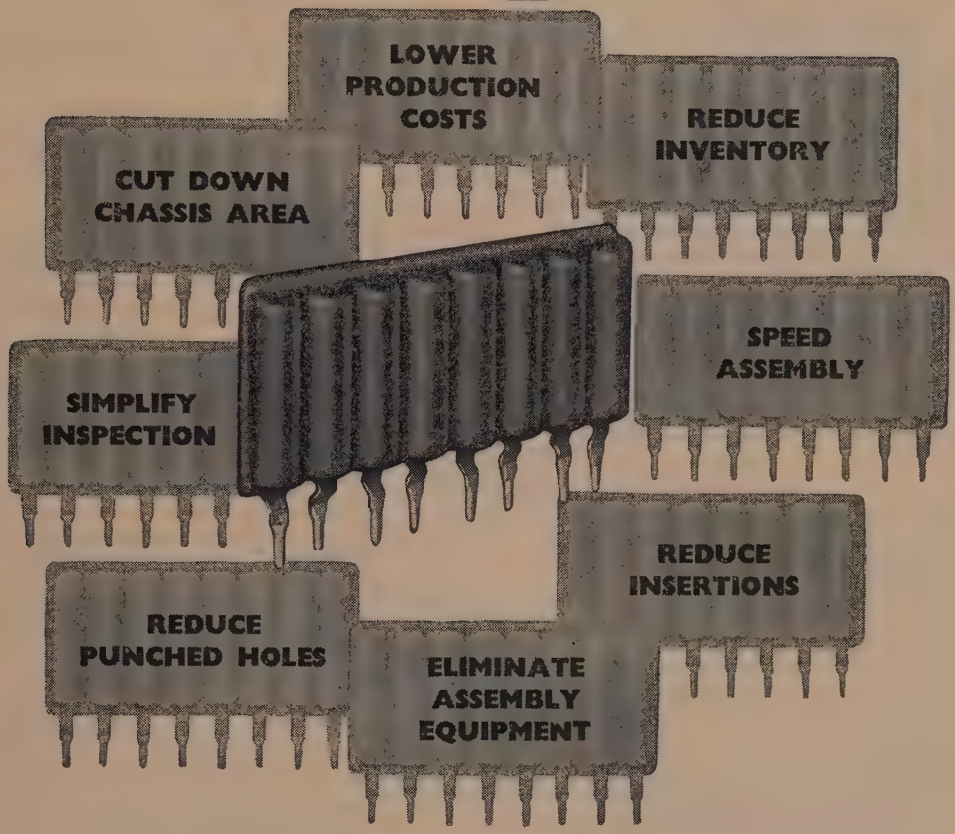
29 Countries use Marconi Radar

MARCONI

COMPLETE CIVIL AND MILITARY RADAR INSTALLATIONS

MARCONI'S WIRELESS TELEGRAPH COMPANY LIMITED, CHELMSFORD, ESSEX, ENGLAN

Pre-assembled Components



The Erie pre-assembled component system, known as "Pac", is a thin vertical module containing standard resistors and capacitors, of proven quality, mounted to a printed wiring board in a stable mechanical assembly, tailored to the requirements of the individual customer.

Besides offering considerable savings in itself, "Pac" paves the way for fully three-dimensional assembly, thus enabling the designer to take the fullest possible advantage of the potential savings in space attendant upon the introduction of shorter, wide-angle, tubes for television.

ERIE* *Resistor Ltd*

★ Registered Trade Mark

PHILIPS

In Science and Industry alike . . .

among technicians, manufacturers and those engaged in the sale of electrical products — as well as among the public at large, the Philips emblem is accepted throughout the World as a symbol of quality and dependability.

PHILIPS ELECTRICAL LTD

Century House · Shaftesbury Avenue · London · WC2

Radio & Television Receivers · Radiograms & Record Players · Gramophone Records · Tungsten, Fluorescent, Blended and Discharge Lamps & Lighting Equipment · 'Philishave' Electric Dry Shavers · 'Photoflux' Flashbulbs · High Frequency Heating Generators · X-ray Equipment for all purposes · Electro-Medical Apparatus · Heat Therapy Apparatus · Arc & Resistance Welding Plant and Electrodes · Electronic Measuring Instruments · Magnetic Filters · Battery Chargers and Rectifiers · Sound Amplifying Installations · Cinema Projectors · Tape Recorders · Health Lamps · Hearing Aids · Electrically Heated Blankets

when heat is the problem



Newton Brothers (Derby) Ltd. use SINTOX in their automatic carbon pile voltage regulators.
One of the most important requirements is the housing of the carbon elements making up the stack. The carbon stack has to be housed in a tube having (1) high dielectric strength, (2) high thermal conductivity, (3) machining properties so that a very fine finish is obtainable on the bore. Electrical connections are made at the ends of the carbon stack so that the stack body itself must be insulated.
Ingress of moisture to the carbon pile is detrimental since it seriously affects the pressure resistance elongation characteristics of the pile.
High thermal conductivity is essential so that heat dissipated in the pile is conducted rapidly to the outside metal cooling fins. Carbon deteriorates rapidly if the critical temperature is exceeded.
Newton Brothers (Derby) Ltd. state that, from their experience after trying other materials such as soda, glass, porcelain, etc., ' Sintox ' has a considerably higher thermal conductivity than any other material they have tested.

Carbon pile voltage regulator. (*Sectional model*)

. . . the unfailing answer is

STAS

Sintox Technical Advisory Service

This service is freely available without obligation to those requiring technical advice on the application of Sintox Industrial Ceramics. Please write for booklet or any information required enclosing blue print if available.

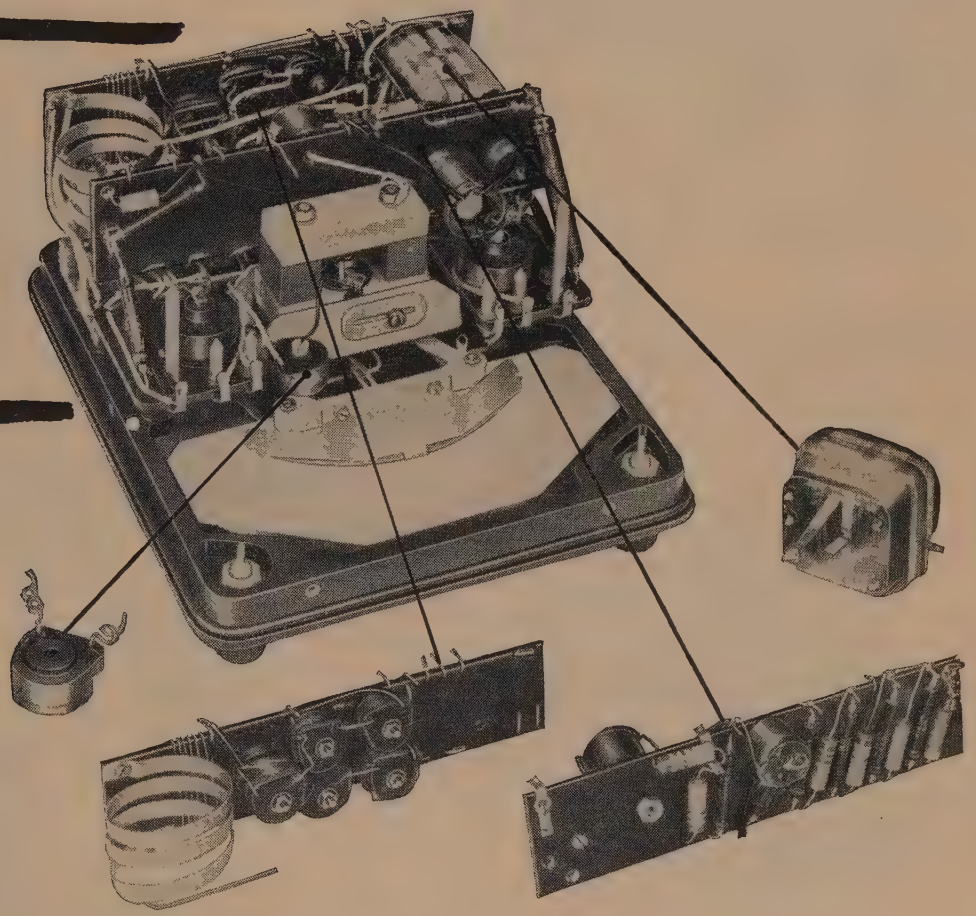
SINTOX

INDUSTRIAL CERAMIC

SINTOX IS MANUFACTURED BY **LODGE PLUGS LTD., RUGBY**

The famous Avometers are possibly the most widely used instruments of their type in the World and have an excellent record of service under all climatic conditions, even at arctic temperatures. In tropical climates, however, there is a constant risk of derangement due to humidity, heat, and the development of fungoid growths. To meet these conditions, the manufacturers of Avometers have produced special types known as Models 7X, 8X and 8(S)X, which are suitable for continuous use in any extremes of heat or cold. In these instruments, certain components are potted in Araldite epoxy resin, which has the advantages of remarkable adhesion to metals, ceramics, etc., good dielectric properties, low shrinkage, resistance to moisture and extremes of climate, and complete freedom from micro-biological attack.

Poles apart



Araldite epoxy resins have a remarkable range of characteristics and uses.

They are used

- ★ **for bonding metals, porcelain, glass, etc.**
- ★ **for casting high grade solid insulation**
- ★ **for impregnating, potting or sealing electrical windings and components**
- ★ **for producing glass fibre laminates**
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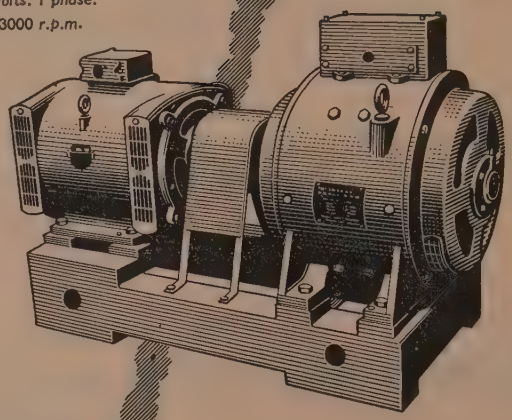
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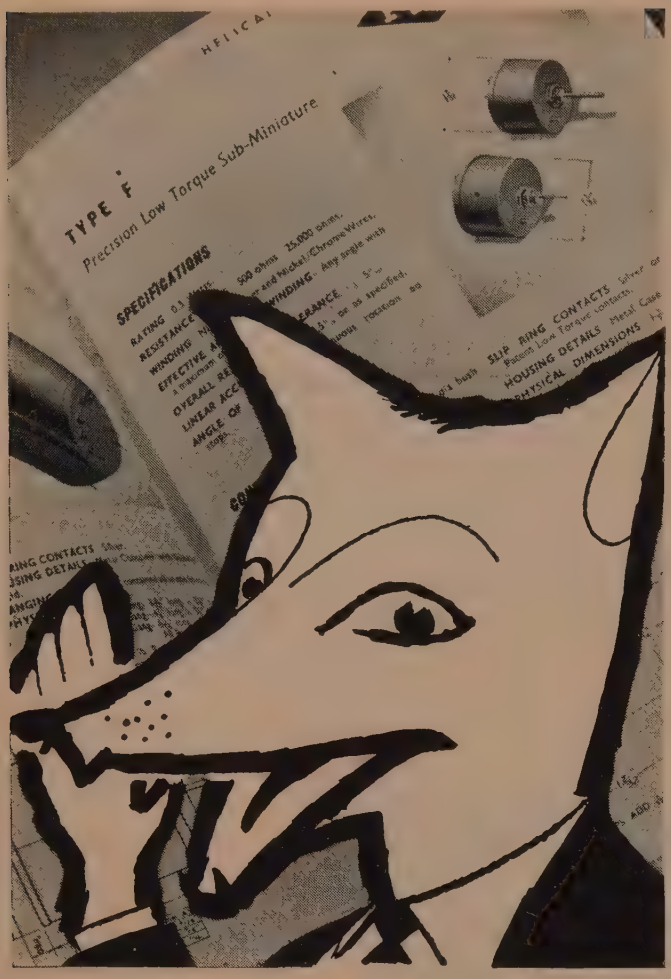
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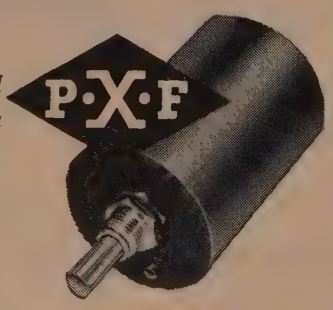
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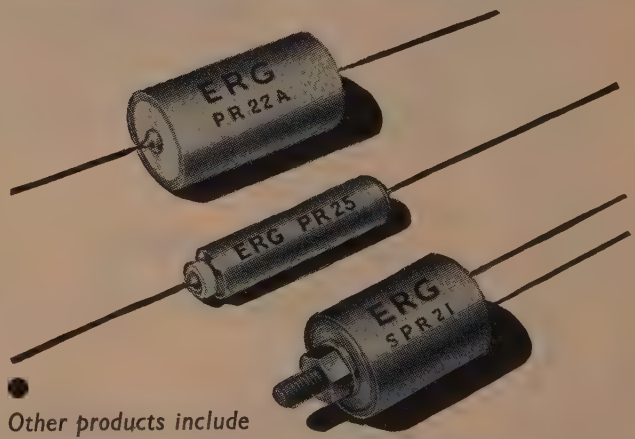
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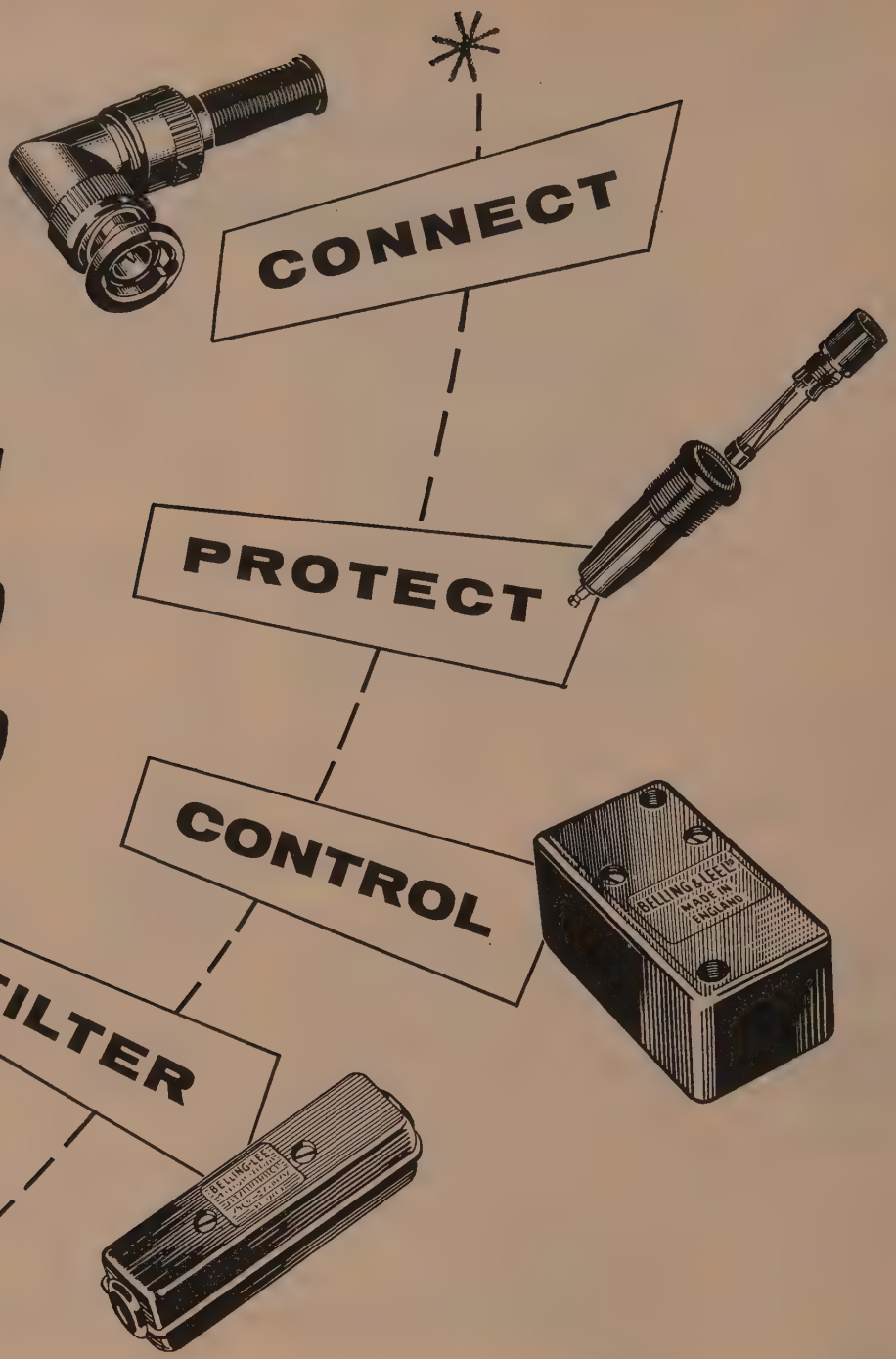
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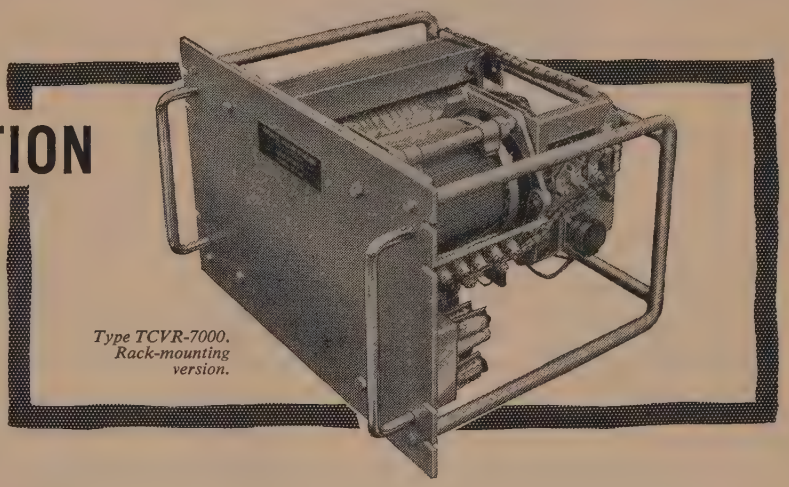
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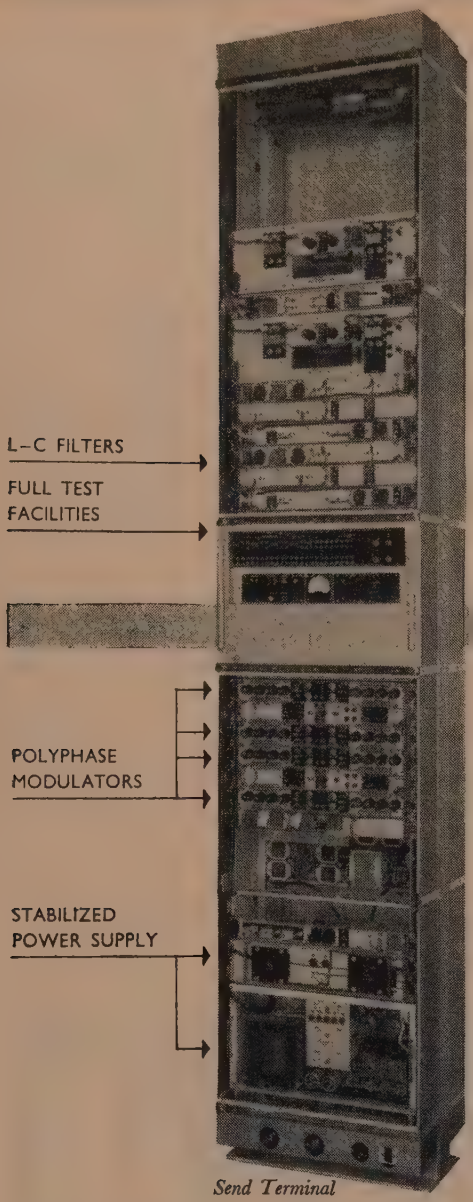
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TAB 7

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An example of the preferred form of bibliographical references will be found beneath the list of contents.

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EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

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Paper No. 2767
Oct. 1958
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INAUGURAL ADDRESS

By S. E. GOODALL, M.Sc.(Eng.), F.Q.M.C., President.

'ELECTRIC CABLES'

(*Address delivered before* THE INSTITUTION *9th October*, 1958.)

At this moment in the career of a newly-elected President of our great Institution, he stands before his friends with feelings so complex that they are not easy to analyse: trepidation is offset to greater or lesser extent by self-confidence; sense of great responsibility by sure knowledge of the support which will be afforded by colleagues, in particular by the immediate Past-President, and sense of inadequacy by determination to do one's best. All these, and more, I am sure my predecessors have felt before me, and I doubt not my successors in office will share them in due course.

I can only express my very sincere appreciation of the signal honour conferred upon me, and assure you that, despite my obvious deficiencies, I will do my utmost in the year ahead to uphold the high traditions and standards established by the many distinguished men who have done so much for our corporate body in previous years. It is a very real privilege to have one's name included in such a list. Quite apart from their technical and professional ability, they share one distinction in common: they have been and are always ready to encourage and help the younger man. This is a tradition which is among the finest cherished by our Institution.

This is not the first occasion on which the electric cable industry has been honoured by the selection of one of its members as President. Moreover, it is not the first occasion on which such selection has been made from the company with which I am associated, and I shall, I trust, be forgiven for a feeling of some pride in this fact.

As it happens, none of these gentlemen took as the subject of his Presidential Address a review of the past achievements, present state of development and future prospects of electric cable making. Reminding myself very firmly of the old and well-known adage, 'Fools rush in where angels fear to tread', I propose to attempt such a review. I believe that a useful purpose may be served if only by the demonstration of the enormous complexity of the technical and other problems that confront the industry to-day, due, in no small measure, to the machinations of such curious bedfellows as chemists and politicians.

Last year on this occasion we were treated to a masterly exposition of the incredibly rapid growth of one of our modern branches of industry—that connected with radio valves. Mr. Goldup chose as his significant date 1904. I make no apology for choosing a somewhat earlier date as my reference point, namely 1812. For it was in that year that Sommering and Schilling conducted a series of experiments in which a soluble material, said to be indiarubber, was first used for insulating wire, following a suggestion made by a Spaniard, named Salva, in 1795 concerning the feasibility of submarine telegraphy. Curiously enough, this first 'cable' developed by Sommering and Schilling was in a sense a power cable as the objective was the detonation of mines. For at least another 50 years, however, practically all development was to be concerned with telegraphy.

It is not my intention to attempt to provide anything like a complete history of the early days of cable making, but it may not be without interest to high-light a few of the more important early events, and, at the same time, to remind ourselves, albeit very briefly, of the concurrent political and social background.

As the 19th century began, we were still very largely living in rural communities. Communication and transport were difficult and slow, and the great drift from country to town had not begun. Some branches of industry were established, of course. For example, it has been estimated that there were 100 000 men and women, and 60 000 children, many of whom were very young, employed in the cotton mills. Such factory regions as there were formed a very small part of the whole, and many people were almost, if not wholly, unaware of the terrifying conditions that were developing, not only in the factories and mills themselves, but also in the slums which were springing up around them. There is no doubt that we have paid very bitterly in terms of mistrust and misunderstanding for many years for the callous misuse of human beings by our industrial forerunners. Despite this ugly blot, it would appear that, for the majority of the population, England was probably a very pleasant place. This was the heyday of the country craftsman, who justly held himself to be as good as any man. For the rich minority it must have been very pleasant indeed. English art was probably at its peak, as such names as Reynolds, Romney, Gainsborough,

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Sheraton, Hepplewhite, the Adam brothers, Capability Brown, and many others, will remind us. In literature and poetry also, great names will spring to mind. This was also the age of reform and revolt against the barbarous practices and customs of the times, so that the leading thinkers were beginning to arouse opinion against the cruelties of the day, even while new barbarities were being invented by many of the industrialists.

No account of this kind, however sketchy, can pass over the fateful year of 1831, in which Michael Faraday ennunciated and demonstrated the laws of electromagnetic induction, and thus made possible the generation and distribution of electrical energy. For the first time, it became apparent that cables would be required for such purposes, as well as for submarine telegraphic communication. Meanwhile, contemporary scientists and engineers were devoting a great deal of thought to the new technology of telegraphy, and schemes for achieving long-distance communication were receiving active consideration.

One of these developments is worthy of note. This was the Wheatstone and Cooke underground system for telegraphs, developed in 1837. It consisted of copper wires, supported at intervals in iron pipes by being laid in grooves in baulks of timber. An installation of this kind was laid in 1838 between Paddington and West Drayton for the Great Western Railway and operated successfully for at least seven years. This may be regarded as the forerunner, not only of the methods adopted by Crompton and others for power distribution, but also of the modern high-frequency coaxial cables used for long-distance telephony and television.

By the middle of the century a number of successful telegraph systems were operating in this country, developed and owned by telegraph companies. Practically all the lines were overhead, and where underground installations were adopted considerable trouble, due to ingress of moisture, had been experienced. Meanwhile, the newly discovered natural gum, known as gutta percha, had been introduced into this country and used for a variety of purposes, mostly domestic. The practical application of this material as a cable insulant was due to Werner Siemens in Germany, and his early trials led eventually to the widespread use of this material for both underground and submarine cables. It is believed by some that Faraday suggested this possible use of the material to his friend William Siemens, who sent a sample to his brother Werner. It is certain that a sample was so sent, and it is interesting to remember that Sir William was, some twenty-odd years later, to become our first President.

By 1851, the first cross-Channel telegraph cable was successfully laid. By this time also several manufacturing companies producing both telegraph instruments and cables were established, and two or three of these in fact were to survive as household names to this day.

Meanwhile, social conditions were changing considerably. Although landed interests were still dominant, industry was expanding at an enormous rate, and the railways, commenced in 1825, were now running 2000 miles of line. Factories, hitherto confined almost wholly to the north, were now appearing near London and other cities. The population of London, only 750000 at the start of the century, was now well over two million. The rich landowners, living in their great London houses, were challenged in wealth and power by the newly-enriched commercial magnates, while at the other extreme many lived in abject poverty in filthy slums, or shared the fate of the down and outs and homeless urchins, who slept in their thousands under the arches of the Adelphi or Waterloo Bridge. The import of cotton was now four times as large as in 1800, and accounted for nearly one-third of the whole trade of the nation. Legislation to limit hours and improve conditions in mills and factories was beginning to take shape, and very slowly some slight mitigation of the worst of the industrial evils was being achieved. Free trade had triumphed as a political doctrine; the threat of revolution was over, and the outlook for trade and industry was fair indeed.

It was against this background that Albert, the Prince Consort, pressed on with his idea for an exhibition of industry in London, which culminated in the opening of the Great Exhibition in Hyde Park by the young Queen Victoria in 1851. Then followed the magnificent achievement which was to establish British supremacy in submarine cable work for the next hundred years, and maybe more. After two tragic and expensive failures, it was in 1866 that a successful transatlantic cable was laid by a company formed primarily for that purpose. It is, I think, of particular interest to record that Sir John Dean, who is now Chairman of that same company, is a Member of the Council of this Institution, Moreover, as I am sure you realize, it is only a few years ago since he played a leading part in that epoch-making submarine cable success, namely the transatlantic telephone cable. With this project, of course, the name of our distinguished Past-President, Sir Gordon Radley, will always be associated.

By 1871, there were sufficient engineers in this country directly concerned with telegraphy to render it desirable for them to form a learned society of their own for the purpose of discussing their mutual technical and scientific problems. In that year, the Society of Telegraph Engineers was formed, and the first meeting took place in 1872. It is with pleasure and pride that I recall that among the list of original members is to be found the name of W. T. Henley. Fifty years later, in 1922, our membership had grown to 10000, and to-day, after a further 36 years, we number over 44000.

The first Presidential Address, given by Sir William Siemens, made considerable reference to the problems of line conductors and insulation. The first paper to make direct reference to submarine cables was communicated by Professor Fleeming-Jenkin, and was published in May, 1872. In 1873, a paper by G. E. Preece (the Secretary), entitled 'On Underground Telegraphs', was read and discussed. It was, however, during a debate held by the Society in February, 1876, that the English predominance in submarine telegraphy was emphasized by Sir William Siemens, who said, 'Submarine telegraphs are specifically English enterprises. I might go further, and say every submarine cable which is now working is, almost without exception, the produce of this country, and has been shipped from the Thames'.

Almost from the inception of the new Society, it became apparent that the interests of electrical engineers would not be restricted to telegraphy alone, and it is greatly to the credit of our founders that they had the foresight to welcome and encourage engineers and scientists concerned with other aspects of electrical work, so paving the way for our own broad conception of the field of electrical engineering. And so it was, in order to connote the extending scope of activity, that the name of the Society of Telegraph Engineers was altered by the addition of the words 'and of Electricians' in 1881. This change was to be considered adequate for only a few years, and in 1888 the Society was renamed 'The Institution of Electrical Engineers', a choice which has stood us in good stead for the last 70 years, and which we trust will continue to serve the needs of succeeding generations for many years to come.

Meanwhile, the use of electricity for lighting was beginning and attention was focused on the possibility of distributing power underground. At first only direct current was employed and low-voltage distribution was only possible up to short distances from the generating source. During this period, many of the systems developed did not use cables, but employed conductors

upported on insulators in ducts or trenches. Where cables is such were employed, rubber soon achieved recognition as one of the best insulating materials.

It was the pioneer work of the young Sebastian de Ferranti hat really blazed the trial for the development of power cables is we understand them to-day. In 1887, as Chief Engineer of he newly-formed London Electricity Supply Corporation, at he advanced age of 22, he was responsible for the conception nd design of the first large London power station at Deptford. This bold scheme broke new ground in many directions. It vas the first successful demonstration of the advantage of high-oltage transmission, 10 000 volts being, according to contem-porary opinion, both highly dangerous and impossibly difficult echnically. Moreover, there were many opponents to the use f alternating current, and little, if any, faith in the newly-nvented transformer. Not content, however, with overcoming ll the practical and personal difficulties associated with such a venture, the young Ferranti was soon dissatisfied with existing ypes of cables, and designed and superintended the manu-facture of an entirely new cable for his mains. In doing so, he roduced the first high-voltage impregnated-paper power cable; type which, although the subject of research and development nd improvement over the years, has remained practically nchallenged for power purposes until the last few years. He lso decided to employ a new type of construction, namely oncentric conductors, and this point alone aroused a storm of riticism. It is, perhaps a sad reflection on our highly, and naybe over-, organized State to-day, that such a young genius vould almost certainly find his ideas strangled by officials, ommittees, regulations and so on—those apparently indis-ensable features of the age in which we live.

By 1900, single-core and 3-core impregnated-paper lead-heathed cables of several different designs were being supplied y several manufacturers, and demand was growing at a very apid rate. This period is, of course, within the memory of ome of our contemporaries, but, nevertheless, it may be of some nterest to remind ourselves of one or two features of the time. General education was beginning to take effect. The school eaving age was raised to 14. The Board of Education was ormed. Free elementary education had been made generally vailable only nine years earlier. Education, housing, transport, aving and, last but not least, street lighting, were now the esponsibility of the newly-formed local authorities. Social esponsibility, hitherto the prerogative of the minority, began to ermeate public life. Public conscience and sense of responsi-ility was at long last aroused, and determined to enforce many elated reform measures.

In this atmosphere it was inevitable that such an industry as urs, uniquely equipped as it is to provide social services and menities of many kinds, should flourish and expand, and as an ssential component of the electrical industry, the cable making ndustry kept pace with this expansion.

Two of the earliest intruders into the telegraph monopoly ere the electric light and the telephone. We have already seen ow the demand for lighting created a need for cable develop-ent. The telephone, invented in 1876 by Alexander Graham ell, soon posed an entirely new set of problems to the cable ngineer. The necessary development was made very rapidly ndeed, once the initial period of neglect of the basic principles ad been passed.

Demonstrations have always been popular as enlivening eatures of our proceedings, and I am sure many of you shared ith me the thrill of listening only a short while ago to the ear-perfect reproduction in this lecture theatre of orchestral usic coming to us from the United States over the transatlantic lephone cable. I was, however, reminded on that occasion of one of the first telephone demonstrations in this country. This was arranged by Sir William Preece in the lecture theatre of the Royal Institution one evening in March, 1878. He arranged to borrow a telephone line running between Southamp-ton and London from the London and South Western Railway, and this was connected to a microphone in a room in Southamp-ton and to a receiver in the Royal Institution lecture theatre. The idea was to hear in London a bugler playing 80 miles away. Alfred, Lord Tennyson was invited to listen and describe what he heard. After a few moments, he reported that he could hear nothing at all. This annoyed the lecturer who caught up the receiver and said that he could hear quite clearly 'The Campbells are Coming'. That he did so was quite remarkable, for the bugler had mistaken the date and did not turn up until the next evening.

Although cable manufacture for telephonic communication proceeded apace from about 1890, it was to be many years before telephone cable engineers understood and began to apply the brilliant theoretical work of Oliver Heaviside, published over the years 1885–1887. He set out quite clearly in his analysis of the problems of alternating-current transmission the signi-ficance of the four factors involved, namely capacitance, induc-tance, leakance and resistance. He stressed the importance of decreasing the resistance and increasing the inductance of lines if long-distance transmission was to be achieved within acceptable limits of distortion and attenuation. His emphasis on inductance was to remain ignored until Pupin in the United States decided to evolve practical means of adding inductance to telephone cables. His solution was to add 'Pupin' coils at intervals to the lines, thus achieving artificial loading. The alternative of con-tinuous loading by laying iron wire along the whole length of the copper conductor was introduced by a Danish engineer, named Krarup, and short lengths of this type were made by the Germans for Denmark in 1902. The first British-made cables of either type were not to appear until 1910, and this loss of initiative was due almost entirely to the lack of technical appreciation and leadership of the Post Office. I have already referred to the very honourable amends made in this field by succeeding generations of Post Office engineers, culminating in the recent transatlantic achievement. The first cables used for telephony were insulated with gutta percha as they were merely adaptations of telegraph cables. In the search for lower leakance, an alternative material, balata, was introduced from South America, and after a great deal of development work on processing, it held the field for submarine purposes until the comparatively recent introduction of polythene. Meanwhile, telephone con-nections between towns and cities were established mainly by overhead lines, while multi-circuit cables soon became necessary in the towns. For this purpose, lead-covered cables were intro-duced, at first filled with insulating material, such as paraffin wax, but soon to be greatly improved by the adoption of the dry-core technique, where the individual wires are covered with dry paper and advantage is taken of the air interstices to obtain low capacitance.

By the beginning of this century, covered conductors and cables were being required in considerable variety for many purposes, and this process has extended over the last fifty-odd years to such an extent that the manufacturers now devote whole factories to different specialized products, and each of these is concerned with hundreds, or even thousands, of different types and sizes. I cannot possibly encompass the whole range in one short address, and will therefore content myself with mention of one or two of the more important high-lights before turning to the second part, in which I propose to deal with some of our present-day problems and developments.

On the power cable side, the increase in power generated and

transmitted has led to continual increase in both voltage and current requirements for cables. As voltages increased it soon became apparent that special means would be required to prevent or suppress ionization within the cable dielectric if any length of service was to be achieved. At first progress was made in improved impregnation methods and materials and in stress control, particularly by screening, but these alone were not sufficient to remove the inherent electrical weakness arising from the effect of heating cycles. As is now well known, these defects arose from the expansion and movement of the cable compound, causing eventual distension of the sheath beyond the elastic limit and the formation of voids in the dielectric in the region of highest stress. The first effective solution of these problems was invented by Emanueli in 1920. He employed a thin mineral oil under pressure from reservoirs at predetermined points in the system. The cable was so designed that free movement of the oil along the cable ensured complete elimination of ionizable voids under all conditions of operation. Although great improvements have been effected by Emanueli himself, and by his Italian and British friends and colleagues, the oil-filled cable remains in principle as originally designed by him. Cables of this type are manufactured in this country by three or four of the leading cable companies, and the majority of the highest-voltage installations, both here and abroad, employ this system. We are particularly glad that Dr. Emanueli is a member of this Institution.

The alternative of using high-pressure gas to suppress ionization was first conceived by Fisher and Atkinson in 1920 and patented in the United States in 1925. Many years were to elapse before there was any exploitation of these ideas in America. In Great Britain, however, four of the major cable companies evolved solutions of the many practical problems. Although development was seriously interrupted by the Second World War, there are now a large number of important installations employing these types of super-tension cables.

One other main preoccupation of the cable maker during this period deserves particular mention, and that is the development of cables for wiring houses, public buildings and industrial premises. The earliest installations were wired with conductors insulated with paraffined cotton, but this material was soon to be replaced by rubber mixtures of varying degree of efficiency.

By June, 1882, there was sufficient concern about the risk of fire to justify the preparation, by the Society of Telegraph Engineers and of Electricians, of their first 'Rules and Regulations for the Prevention of Fire Risks from Electric Lighting'. These were very short and dealt mainly with the necessity of eliminating moisture and making good conductor joints. Cables are dismissed in one sentence, 'All wires used for indoor purposes should be efficiently insulated', and by a reference to the desirability of affording protection against abrasion and 'the depredations of rats and mice'. There was also a footnote urging frequent testing, as 'escape of electricity cannot be detected by sense of smell as can gas'. Incidentally, an external switch was advocated, so that the supply could be cut off at once in the event of the potential difference between any two points in the house exceeding 200 volts.

By 1897, a new set of 'Fire Rules' was published. This had been prepared by a technical committee comprising the whole Council together with other experts. It was now concerned, not only with lighting, but with the supply of electrical energy. Various systems of wiring were being advocated, and from these two emerged which were to survive the test of time; these were the steel conduit and the lead-sheathed systems. Great improvements in the production of appropriate rubber compounds were effected, together with improved methods of applying the insulant and sheath, and the subsequent vulcanization process.

As the years passed, electricity spread as a source of pow in many industries, including mining, where very special p cautions were required, resulting in the development of spec types of cables. The introduction of electricity into ships, bo civil and naval, produced a new batch of problems. Lat additions to the list include aircraft and rocket missiles, a doubtless we may anticipate new demands upon us as a resu of man's desire to travel in space.

Another group of cables has been required for signalli purposes, first, of course, for the railways. The First Wor War created a considerably enhanced demand for cables this type, but no other very notable changes in technical requir ments arose during the period 1914–1918. The normal produc of the industry, however, continued to be in great dema throughout the period of the war. So much so, that in 1918 official committee reported as follows:

> The manufacturing of electrical machinery and apparatus Great Britain has been with few exceptions far from prosperous . The notable exception has been cable making, which has been co sistently successful in maintaining its lead, both in the quality its manufactures and in financial results, and has been able to ho its own in the world's markets.

Between the two wars, although considerable technical pr gress was made, there was no very radical change in t materials employed. Manufacturing techniques and process were improved. National and international standardizati proceeded apace. Specifications were tightened. Considerab economy in the use of materials was effected. Business w conducted at a profit level which enabled the leading man facturers at least to keep pace with plant and process improv ments. Despite keen competition, and the gradual increase the number of companies engaged in cable work, trade expand steadily both at home and abroad, except, of course, during th general trade slump in the early 'thirties. It was in the field super-tension power cables that the most notable technic advances were achieved, and I have already made reference some of these. A number of important Institution papers we read and discussed by cable engineers and by cable-us engineers, and good attendances, with the debate ranging fro friendly criticism to downright denial, could be guaranteed.

During the whole of the process of expansion in cable busines both in quantity and type, parallel needs had developed for th many fittings, accessories, pillar units, fuse units, joint boxe sealing ends, etc., that were required. This has now become highly technical and specialized trade in itself. Although the are now a few companies concerned with some aspects of th business who are not cable makers, the largest cable maki concerns have built up very considerable departments or factori for these purposes.

The Second World War had far greater effect on the work the cable engineers than the first had done. The first impa was a sudden demand for high-frequency cables, for radio an radar. As the war progressed, higher and higher frequenci were employed and the requirements became very stringen Great accuracy and consistency in manufacture became essenti and the new plastic material, polythene, came into the picture

The difficulty of obtaining adequate supplies of raw rubb necessitated a rapid examination of the possibilities of synthet materials, including the now well-known polyvinyl chloride, p.v.c.

In addition, the larger companies were called upon to develo cables for special purposes, including the so-called 'buoyan cable for dealing with mines at sea, and, of course, the famo H.A.I.S. 'cable', which consisted of a strongly reinforced co tinuous lead tube laid across the Channel to supply petrol the advancing allied armies. I do not propose to elaborate

ese and other war-time cable achievements, as these have been ell recorded and documented in the Institution *Proceedings* id elsewhere.

Up to the beginning of the war, certain basic materials and rocesses had become so well established that it had begun to ok as though they would never be seriously challenged. Since e end of the war, however, the position has changed very astically, and I propose to draw your attention to some of the ore important of these changes, which have had a profound fect upon the general economy of cable making.

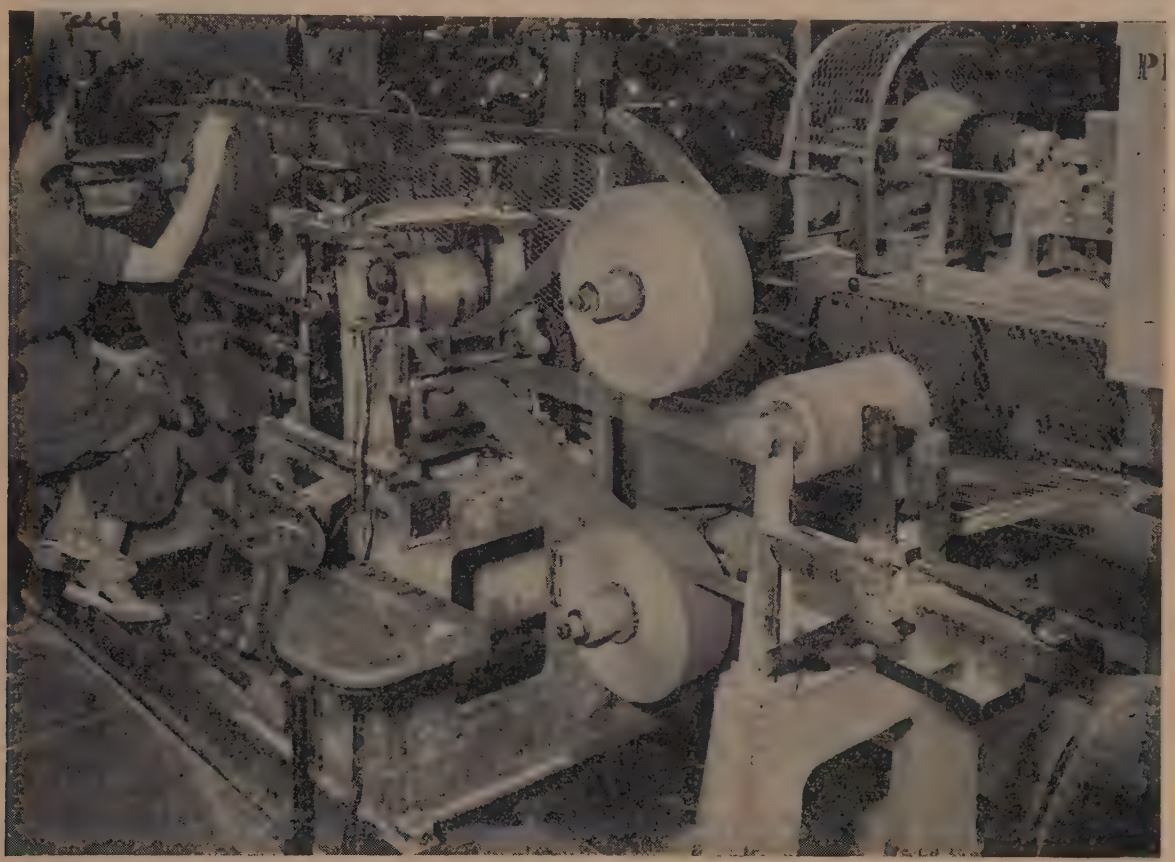


Fig. 1.—Covering of conductors by the longitudinal method.

The primary factors which have brought about these changes e:

(i) Introduction of new plastics.
(ii) Need for greater economy in the use of materials.
(iii) Introduction of synthetic rubbers.
(iv) Advent of entirely new processes due to rapid growth in the cable-plant manufacturing industry.
(v) Development of automatic control systems.
(vi) Competition in world markets from Continental manufacturers.
(vii) Increasing demand for cables for special purposes and arduous conditions, such as high temperature, low temperature, operation after fire, etc.

The first example which I have selected is concerned with the nufacture of the smaller sizes of rubber-insulated and -sheathed bles, such as those with which we are all familiar in domestic plications.

The well-established method of covering, usually called ngitudinal', includes the following processes. After prepara-n of the appropriate rubber compound in the form of slabs, calendering process, similar to that used in paper making, is employed to produce thin uniform sheet. This sheet rubber is cut into long strips which are rolled up and mounted, so that they can be fed in pairs between grooved rollers. The wires to be covered are passed through the rollers in the grooves and between the two strips of rubber. By appropriate design of the grooves and adjustment of the gap between the rollers, it is possible to cover the wires with seamed rubber. As many as 36 wires can be passed through the same number of grooves in one pair of rollers. This process can be repeated in tandem by using two more pairs of rollers in the same machine, thus producing the well-known 3-layer dielectric. Fig. 1 shows one of these machines in operation. The covered wires are taken up on reels at the far end of the machine. Subsequently, these covered wires, or cores, are rewound on to drums which are wheeled into a large vessel into which low-pressure steam can be fed to effect vulcanization of the rubber.

A further rewinding process is necessary after vulcanization before the finished core is ready for the further operations necessary to produce a finished cable. It will be appreciated that this method is far from efficient, involving as it does several discontinuous processes, particularly at the longitudinal-covering machine itself, which has to be stopped each time one of the coils of strip rubber runs out.

The modern alternative, developed since the war, is known as 'continuous vulcanization'. In essence it may be described as follows. Rubber compound in the form of thick strips is fed into the hopper of a rotary-screw extrusion machine, so designed that the compound is forced on to the wire to be covered as it passes through the 'head' of the machine, at a fairly high speed. Immediately on leaving the head the covered

wire passes into a long well-lagged steel tube containing high-pressure steam. Lengths of the order of 150 ft are usually employed. At the far end of the tube, the now vulcanized core is passed through a high-pressure water bath and wound up on to large spools. In its most highly developed form, as illustrated in Fig. 2, this plant is run continuously for a whole working

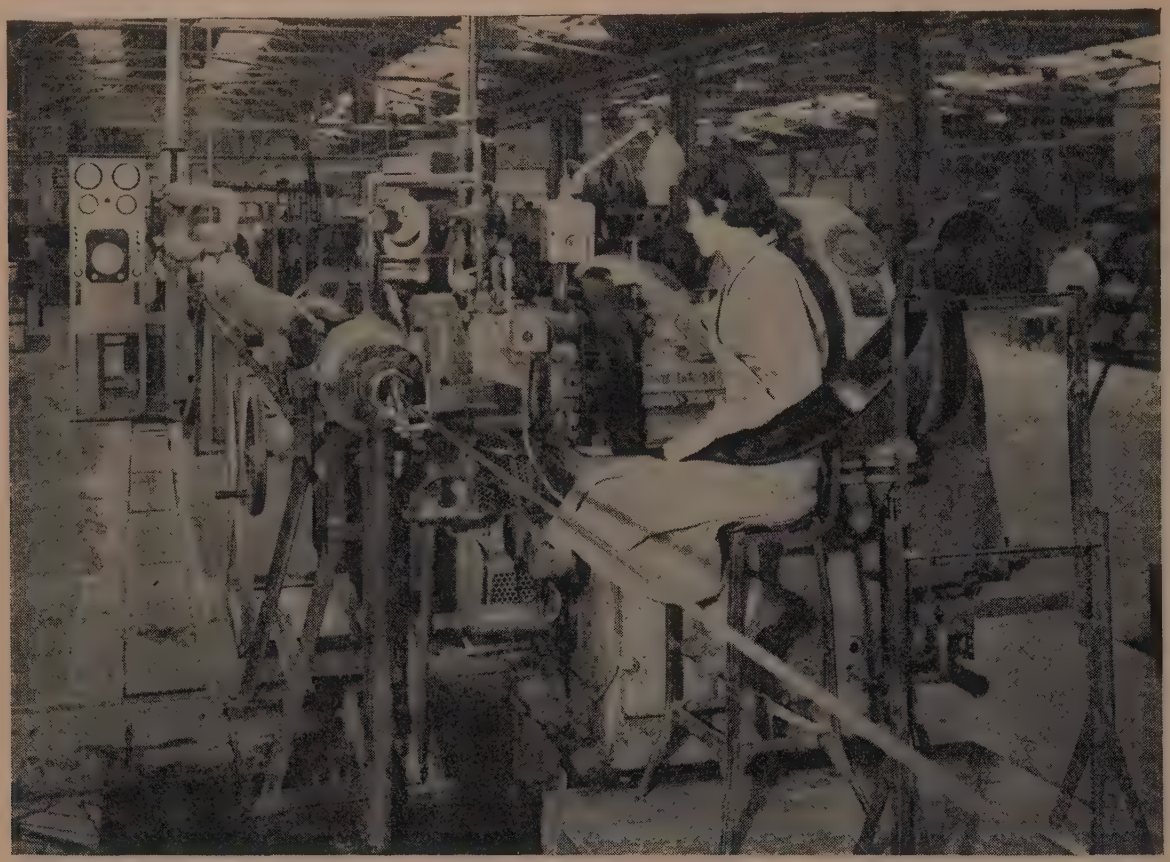


Fig. 2.—Continuous vulcanization plant.

shift of eight hours, or even longer. Arrangements are provided for feeding in the bare wire from a succession of drums without any interruption of the extrusion process. Similarly, at the far end, take-up on to a succession of drums is provided without any necessity for stopping the machine. Moreover, fully automatic control is provided, so that any variation in the thickness of the rubber covering is immediately corrected by an automatic adjustment of speed, effected by electronic control equipment. The finished core is produced to very close tolerances. Incidentally, this equipment is usually designed and developed by the cable maker. Some of the leading cable makers now have several complete units of the kind I have described, not only for the production of the core but also for a range of small- and medium-size sheathings. For larger-diameter sheathing, extrusion of the rubber compound is employed, but the vulcanization is discontinuous.

Unfortunately, it is not possible to produce the whole output of small- and medium-size rubber core and sheathing by this method. The reason is purely one of economics. Due to the large variety of size, colour and type of rubber core and cable required, it is not always possible to ensure a sufficiently long run on one continuous-vulcanization unit to justify set-up. The manufacturer's occasional reluctance to accept a change of colour coding for a particular application will, I trust, now be appreciated.

Naturally, a transition of this magnitude has not been achieve without overcoming a multiplicity of new technical problem many of which have only been solved by introducing high precision engineering methods. Very considerable chemica problems also required solution, for the compounds evolve for the older process were not found to be entirely satisfactor

for the new one. Very close collaboration between enginee and chemists was necessary to perfect the processing and ensu high-quality production. Some consequent changes in t appropriate British Standards have been made comparative recently.

Of the several plastic materials produced in the last twenty so years, polyvinyl chloride has so far proved to be the mo important for general cable-making purposes. Direct extrusi methods are employed for both core and sheath of a wide varie of cables, many of which were formerly produced solely using rubber. At first, attempts were made to extrude p.v by using plant designed for the extrusion of rubber compound and although some progress was made, it was soon realized th specially designed plant would be required for efficient pr duction. Considerable progress had been made by one or tw plant manufacturers in the United States; consequently, duri the war, plant was imported from America for this purpose a allocated to several British cable makers. Since that tim however, improved plant has been evolved in this country, a in some respects at least it offers advantages by comparis with American practice.

The preparation of p.v.c. compounds for the different purpos required by users is a highly complex and specialized study itself. Some p.v.c. compounds are now obtainable from t chemical industry in a form suitable for the extrusion proce

hose cable makers who use large quantities and/or supply ecial-purpose cables, find it desirable, or necessary, to purchase e polymer, plasticizers, stabilizers and other ingredients, and olve their own compound formulae. In addition to the aborate mixing plant required, further equipment is necessary order to produce the compounded p.v.c. in suitable pellet, or anule, form for feeding into the hoppers of the extrusion achine. Mixing plant as used for rubber compounds has also en employed successfully for p.v.c. compounds. Fig. 3, how-er, shows one of the most modern plants recently installed ecifically for the preparation of p.v.c. compounds. Not only es this installation produce the compounded p.v.c. in suitable rm by a continuous process, but specially designed arrange-ents are incorporated so that the proportions of various com-onents can be altered by pre-setting, and thereafter these roportions are maintained automatically.

While on this subject, it may be as well to mention another rowing use of p.v.c. which has recently required further capital vestment, namely anti-corrosion servings. In order to protect e lead or aluminium sheath of a cable, either from the corrosive fects of soil waters or from the acids produced when textile rvings rot through bacterial attack, it is necessary to provide rotective layers over the sheath and/or, where the cable is rticularly important or conditions are very bad, protection ver the armoured tapes or wires. It is often sufficient to rovide lead-sheathed cables with bitumen compound held in sition by layers of paper and cotton tape, or p.v.c. tape, but r aluminium sheaths and for the better protection of lead eaths, a more impervious layer is to be preferred. Rubber as been used extensively for this purpose, but more recently truded p.v.c. sheaths have been successfully employed. This as necessitated the development of large p.v.c. extrusion achines which are installed in the paper cable factory.

The other plastic material which is of major significance in e industry is polythene. I have already mentioned the intro-uction of this material for high-frequency purposes. It is very itable as a dielectric for low-voltage use owing to its excellent ectrical properties. For such purposes as house wiring, fairly rge quantities of cable have been used in this country, the olythene core being protected by p.v.c. sheath. Fortunately r the cable makers, relatively minor modifications to p.v.c. trusion plant are required for the production of small poly-ene core. The fact remains, however, that they are now roducing at least three varieties of these cables employing fferent materials for the same conditions of service. There e one or two important differences in the behaviour the three materials which should be borne in mind when e problem of choice arises. Of these, I would mention the llowing.

Ordinary grades of polythene melt at temperatures slightly ver 105° C, so that cables using this material are more prone damage by sustained overload or short-circuit. It is true at some of the high-density grades now becoming available ave slightly higher softening temperatures. Moreover, con-derable improvement can be obtained by irradiating with eutrons in an atomic pile, or with electrons from a linear celerator or high-energy Van de Graaff generator. Such treat-ent effects cross-linkages between the molecular chains and eliminates the sharp melting-point. Instead, the material comes rubber-like at temperatures of the order of 150° C. nfortunately, the process is expensive, and it appears unlikely at polythene treated in this way will be used for anything more an special applications. Polyvinyl chloride, on the other hand, comes softer as the temperature increases, and while it has no arp melting-point, is subject to the disadvantage that serious formation under mechanical stress could occur at the higher temperatures. Neither material is able to withstand the overload conditions that can be tolerated by vulcanized rubber, without serious consequences.

Polythene has also been employed successfully for higher voltages up to 11 kV, although its use has been very restricted in this country up to the present.

In addition to plastic materials, a number of synthetic-rubber materials are now available. The monomers which form the base of these materials are usually obtained from the petroleum base by the cracking process, in which the complex hydro-carbons are broken down into simpler ones by being passed over catalysts at appropriate temperatures. Developments in this field have been more rapid in America than here, and although there was considerable need for synthetics during the war, interest has waned since, except for special applications and for export purposes. The styrene-butadiene type, usually referred to as GR/S, has no particular advantages over the natural product and is now very little used in this country.

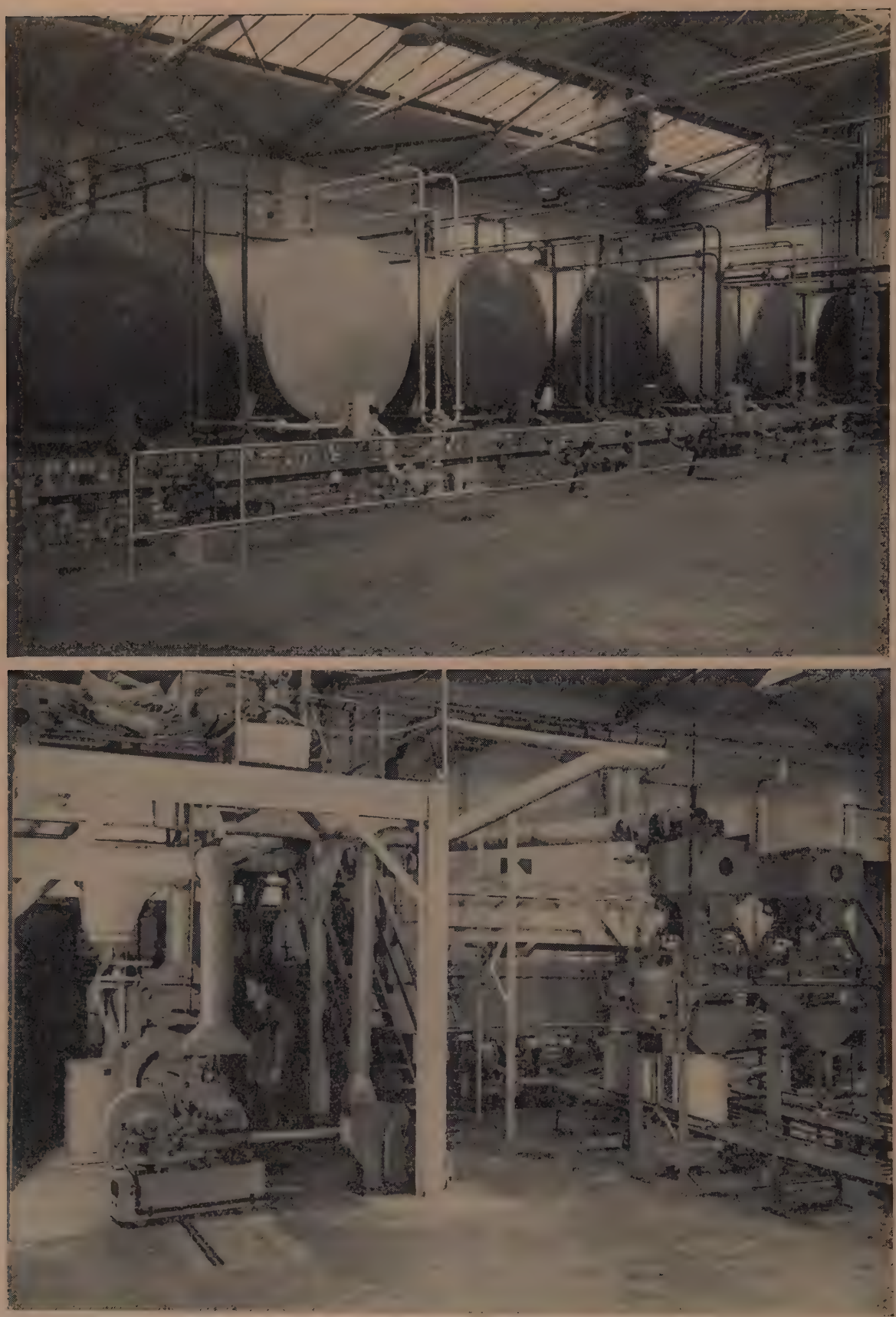
Polychloroprene, or Neoprene, which contains about 35% of chemically combined chlorine, is used for applications where good resistance to oil and water is required. It also has the advantage that flame does not spread along the material. It is, however, inferior electrically and is therefore usually employed for sheathings and not for dielectric purposes. Fortunately, plant and process problems are relatively minor.

Butyl rubber, which is a copolymer of iso-butylene and isoprene, is receiving increasing attention, particularly as it is specified for certain high-voltage export purposes. This material is resistant to oxidation and is of low chemical reactivity. Processing is, however, by no means simple.

Another particularly important synthetic is silicone rubber. This may be regarded as half organic and half inorganic, as the backbone of the molecular chain is a silicone-oxygen linkage, similar to quartz. It offers certain unique advantages, and for this reason is now being used in H.M. ships and in aircraft. It has exceptional resistance to heat, and will operate indefinitely at 150° C, and at considerably higher temperatures for short periods. After a fire, cables will continue to function if not disturbed, as the residue is largely pure silica. Flexibility is retained down to −70° C. The electrical properties are similar to those of natural rubber. Again special processing is required. Fairly large quantities of cables employing silicone rubber are now being produced.

From the foregoing examples, it will be evident that there has been a considerable strain on the cable makers' capital resources since the war, and that the demand by the industry for highly specialized scientists and technologists has also increased materially. Specifications for existing types of cables are under constant revision, and every endeavour is made to meet the users' demands for more economic construction for the same duties or for extension of permissible use for the same construction. None of these objectives can be achieved without a continuing programme of trial, experiment and research, and for effective results constant collaboration between the different interests concerned is absolutely essential.

In one respect the cable-making industry, and indeed the whole electrical industry, of this country has been fortunate. We have been assured so far of an ever-increasing home market on which to base a flourishing export business. Modern political trends, however, suggest that we may soon be facing Continental competition in our home market. It is true, of course, that should this happen Continental markets will also be open to us. Whether the redistribution of trade would be of benefit to British cable makers depends on many factors outside the scope of this address, but one important consideration, namely that of standards, is worth examination. Our own British Standards



(*a*)

(*b*)

Fig. 3.—P.V.C. compounding plant.
(*a*) Storage vessels for raw materials. (*b*) Compound-making plant.

r cables have been built up over the years on the basis of perience of successful service under our particular conditions installation and use. They are established and modified by S.I. Committees, on which representation by users is pre-ominant. Much of the experimental work upon which they e based is conducted by the principal members of the Cable akers Association, who have established a structure of tech-cal committees to provide this and other services for cable ers. In addition, valuable basic information and data are ovided by the staff of the Electrical Research Association, ho have always been closely associated with cable problems, rticularly those which have to do with rating. Our standards ve formed the basis upon which many of the Commonwealth untries have developed and are developing standards to meet eir own requirements. Periodic Commonwealth conferences e held at which mutual problems are discussed, and whenever ssible common policy is adopted. On the Continent, there e one or two sets of standards which are different from our vn in many respects. At the present time a great deal of tention is being devoted to the possibility of reconciling these fferences in whole or in part. There are, of course, differing inions in our industry and among the users concerning the sirability of adopting Continental standards in this country. or, let's face it, that is really what reconciliation of differences ill very largely amount to, since we speak as only one voice many of the international conferences, such as I.E.C. and .E.E., where such matters are discussed. My own view is at the British cable user would be most unwise to agree to ch drastic changes without very careful consideration of all e detailed factors involved. The whole subject of standards nd standardization is very complex. Over-standardization and rematurе standardization should always be avoided, as they tard technical progress and discourage research and develop-ent. On the other hand, our own British Standards provide e best possible safeguard and assurance of high quality, good rformance and long life.

And now what of the outlook for cable making in Great itain? First, let us look at some of the technical possibilities nd objectives.

Commencing with power cables for distribution purposes, e demand for the comparatively new non-draining paper ble has built up rapidly. This is the type in which the impreg-nt is a waxy material which is solid at operating temperatures. o-day an appreciable proportion of all low-voltage and high-oltage cables up to 11 kV are of the non-draining type, and there ems to be every indication that the demand will increase.

Meanwhile, considerable interest is being shown in the possi-lities of plastic mains cables. P.V.C. has, of course, been used r some years for low and medium voltages for industrial instal-tions. The Area Boards and the C.M.A. have been engaged cently in a joint study of the potentialities of p.v.c. mains bles, and a draft specification for further discussion has been bmitted to the B.S.I. This covers p.v.c.-insulated wire-moured cables for use up to 1 100 volts, and provides alter-tive beddings under, and servings over, the armour. One ternative in each case is extruded p.v.c. It would appear that me small economic advantage may be achieved by using these bles, but, of course, a cheaper form of construction could be nployed if it were possible to dispense with the armouring and e a concentric neutral. The problem of live jointing for rvice conditions is by no means a simple one, however. A stem employing these cables would involve the use of protective ultiple earthing, and this would present considerable diffi-lties to the distribution engineer. It must be remembered at any plastic is likely to be inferior by comparison with paper der severe overload or short-circuit conditions. It is evident that it may be some time before these cables are used very extensively in this country, although I am confident that we shall see some installations of appreciable magnitude in the near future.

At higher voltages, up to 11 kV, polythene has been used successfully as a dielectric material despite the difficulty of ensuring an entirely void-free extrusion. For this reason, great care is essential during processing, and highly sensitive ionization-detection methods are used as a routine check of the homogeneity of the extruded material.

There has been discussion recently in national and international circles concerning the potential use of polythene for very high voltages. At present it appears unlikely that any extruded plastic material will be used for such purposes except for submarine cables, where polythene may well offer some advantages, particularly for direct-current transmission. It is noteworthy that views were expressed at the C.I.G.R.E. meeting this year that the limits for polythene were likely to be 33 kV a.c. and ± 200 kV d.c. For modern conditions of greater power and higher voltages, it is now evident that the highly developed oil-filled cable system can meet all the requirements which are likely to arise for many years to come. Within limits, this is also true of some designs of gas-filled cable. A good deal of money, time and energy has been devoted in recent years in attempts to produce super-tension cables capable of operating at high maximum working stresses. It is obviously undesirable to go too far in this direction, as the attendant operating risks are of necessity increased. Moreover, the apparent economy in price afforded by removing two or three layers of paper from the dielectric may be more than offset by other operating economics when the true value of increased running costs is taken into account. I believe the C.E.G.B. engineers are now, quite properly, taking these factors into account.

The drive for economy in use of materials in the manufacture of cables is now running parallel with the drive for economy in the use of the cables themselves. Although it would be relatively easy to determine the maximum current which should be carried by a cable under given conditions of installation, it is by no means so simple to state appropriate limits in practice, as most cables are subject to varying loads often in a daily cycle. They may also be subject to overload for long or short periods, particularly in times of emergency, and may have to carry occasionally short-circuit currents of considerable magnitude for periods dependent upon the rate of operation of the protective apparatus.

Until comparatively recently, most supply engineers have adopted a fairly conservative policy with regard to choice of cable size for a given duty, and there is little doubt that a proportion of the cable buried in the ground in this country has never reached the maximum operating temperature for which it was designed. On the other hand, it is well known, although seldom if ever officially admitted, that some distribution cables, particularly at the extremities of rapidly growing load areas, have been subjected to considerable overloads. In view of the necessity for national economy in such matters, however, some important investigations on cable utilization are now being conducted by the Electrical Research Association in conjunction with the Central Electricity Generating Board, the Area Boards and the cable makers. The primary objectives are to determine the effects of practical operating conditions with a view to better utilization of cables already installed, and to provide a more satisfactory basis for efficient specification of cables for new systems. At the same time, work is in hand to determine the limitations imposed by short-circuit considerations.

Future developments in cables for wiring purposes are unlikely to be revolutionary. The trend towards greater use of plastic

materials will undoubtedly continue. There will probably be continued effort in the direction of reducing dimensions, made possible largely by improved processing control methods.

As I have already indicated, a good deal of attention is being devoted to the development of cables capable of withstanding extremely arduous conditions. Much of this work has been concerned with cables for modern aircraft, where such considerations as lightness, toughness, ability to withstand extremes of temperature, or even to operate after fire, and to resist attack from modern fuels and lubricants are of importance. Some of the latest types of cables for such purposes are proving to be very successful in service, and there is little doubt that even the most difficult conditions imposed by aircraft designers will be met effectively.

Expansion of the use of silicone rubber for applications where higher-temperature operation is desirable, and/or where temporary operation after fire is required, will no doubt occur. For most purposes, it will be necessary to protect the insulation as the material is not resistant to all fuels and lubricants.

Improvements in p.v.c. compounds will extend the range of usefulness of this material, particularly for operation at slightly higher temperatures without material reduction in useful life.

All this, and much more, will undoubtedly be achieved by cable engineers, and we may be sure that we in this country will continue to play a leading part in many of the future developments.

There remains, however, for the cable-making industry as a whole, one fundamental problem which certainly must be tackled if we are to be able to face competition from abroad, both in home and export markets. It will be evident from the very limited range of examples that it has been possible to encompass in this address that the two bugbears of cable making are alternatives and variety. By this I mean alternative designs and materials for the same duties, and variety of size, type, colour, finish, etc., in the vast range of products. The former has particularly afflicted us since the last war and has led to constan demand for new plant and plant modifications far outstrippin the gradual growth in gross demand for cables. The result ha been that the industry as a whole now possesses surplus plan for many operations, although few, if any, of these operation are wholly obsolete.

If effective progress is to be maintained, two steps woul appear to be necessary. First, the industry must be prepare to face the consequences of rationalization of production. Th means effective regrouping of manufacture, and obvious requires close collaboration in one form or another between th different companies concerned. Technical collaboration ha improved considerably in recent years, but this alone is no enough, important as it is to improve still further in this respec Second, the cable users in their own and in the national interes must be prepared to accept some measure of restriction o choice. To this end, standardization must be directed toward the elimination of unnecessary complication and not aim at th inclusion of every twist, turn and vagary that can be thought up

Finally, let us examine very briefly the possible scientifi future to see whether there is any indication, even on the remot horizon, of the art and technology of cable making becomin redundant. As I see the position, there is no such indication The atomic energy age, now so actively beginning, is makin greater demands upon the whole electrical industry, includin cable making. University laboratories are beginning to prob the possibilities of the thermo-electric generator as a source o power direct from heat. The fuel cell is also receiving attentio as another possible source of small quantities of electric powe direct from chemical reaction. The fact remains, however, tha no convenient alternative to electricity capable of providin such a wide range of services is even remotely envisaged, and s far there is no indication that electricity can be guided an distributed, save in very minute quantities, by any convenien means other than the electric cable.

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RADIO AND TELECOMMUNICATION SECTION: CHAIRMAN'S ADDRESS

By G. MILLINGTON, M.A., B.Sc., Member.

'RANDOM THOUGHTS OF A PROPAGATION ENGINEER'

(ABSTRACT *of Address delivered 22nd October*, 1958.)

At the beginning of my career I had the good fortune of coming under the guidance of one of the great men of radio. I refer, of course, to T. L. Eckersley, and it is my deep regret that he is now unable to take any part in the work to which he contributed so much, both in theoretical and practical research. Otherwise the honour of being elected Chairman of our Section would surely have been accorded to him.

It is customary for your Chairman in his address to review some subject with which he is particularly acquainted, but I have met an immediate difficulty. My main interest in radio, acquired from T. L. Eckersley, is in wave propagation, and much of the theoretical work is inevitably mathematical and of a forbidding nature when carried out with all the rigour of the game. It is not unfair to say that propagation research is sometimes regarded as an academic study remote from the realities of radio and often used as an excuse for erudite exercises in abstruse mathematics. I have toyed with the idea of taking as my theme the basic nature of propagation, showing, for instance, how much of the design technique in the engineering of communication systems is concerned with the limitations imposed by the ionosphere and troposphere. It seemed to me, however, that this might form a subject for one of the general meetings of our Section, bearing in mind the 'new look' of our programme for this Session. I have therefore decided on another course, namely to consider in turn a number of loosely related topics and to illustrate them from the field of propagation.

Technical Literature

One of the greatest problems facing research workers is the flood of papers that ceaselessly pours from the technical Press. Not only is it difficult to avoid overlooking important papers, but it is often impossible in the time available to read them with discernment. Even in a very specialized study one may be forced to put aside, almost in despair, contributions that are obviously closely related to the work in hand. More especially is this so with mathematical papers, where the complexity of the argument may preclude any quick assessment of its significance. With the rapid advances in technology, it may well be inevitable that papers will appear in ever-increasing numbers, but I should like to venture some comments on the situation as I see it.

Anyone who contemplates writing a paper for publication should ask himself if it is really necessary and whether the information he wishes to impart is likely to be useful to others and to stimulate further advances. Moreover, greater attention should be paid to the way a paper is written. Admittedly many authors have difficulty in finding the time to produce a paper at all, so that the first form in which it is composed may in effect be the finished product. But there are few who are so gifted that they can really 'hole out in one', for, apart from the question of style, there is a grave danger that the author may be so familiar with his work that he will tend to forget that the reader is not already equally well informed. All too often in such cases, passages may have to be read several times before it is possible to infer what is intended.

It is essential that the busy engineer should be able to assess quickly the probable value of a paper in his field of interest. A good summary or abstract is a guide, but it should be possible to appraise a paper by looking it through if it is well set out and lucidly written. This is, in fact, all that referees should need to do, and it is usually the badly written but not obviously unsound paper that is subject to a heavy delay at this stage of publication.

This problem is most acute in the case of papers in which a physical problem is solved by mathematical analysis. It is now the practice to relegate as much of the mathematics as possible to appendices which need only be read by those interested in such details, but even in a paper which is essentially mathematical in character, the main line of the argument and the general conclusions can sometimes be given in a section preceding the detailed analysis, so that when he reaches the mathematics the reader is already well acquainted with the thought driving it along.

It is unfortunately true that the professional mathematician is not always the one best equipped for tackling physical problems. A knowledge of the principles involved and an insight into the probable form of the answer will often enable the mathematics to be cast into the best shape for practical application. There are some notable examples in ground-wave propagation where a formally correct solution has been obtained in which the physical significance has been obscured by the method of presentation. In some cases the author has not fully appreciated what he has achieved, judging by his failure to draw conclusions from the mathematical results that have subsequently to be established by the engineer who knows what to look for from his practical experience. The authors of mathematical papers should consider carefully whether they have expressed their ideas and conclusions in the form best suited to the engineers for whom they have presumably done their work.

It is, however, possible never to be satisfied with one's efforts and to keep on delaying publication in order to include some improvement or new development. It is admittedly vexing after a paper is in the press to think of some change of notation that would have added elegance to the mathematics, or to discover some way of extending the analysis to embrace an outstanding aspect of the problem in hand; but such delay may lead to the author being forestalled in publication by someone else working independently in the same field—not that priority in itself is as important as some consider it to be. A balance may therefore have to be struck between the hasty publication of an ill-considered and indifferently written paper and the holding-up of work that may be of great value to others even in an imperfect state.

Problems of Refereeing

I have already hinted at the task of the referee. We are fortunate in our Institution in having a system of refereeing

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which maintains a high standard of publication. In spite of the delays that are caused when an overworked referee fails to act promptly, and when authors are required to make considerable revisions before their papers can be accepted, we should be very cautious about any general relaxation in this matter. It is inevitable that, with the increasing number of symposia and conventions being sponsored by our Section, some latitude should be allowed in order to meet the tight time schedules and not to reject if at all possible any obviously important contribution of great topical interest. But the fact that in retrospect an occasional paper is seen to be below par in style or content only serves as a salutary reminder that our refereeing system is fundamentally sound.

There are, however, two problems that beset referees from time to time on which I wish to say a few words. The first concerns the paper that presents some strikingly new material but which is so obscure that no one can understand it. There are many examples, not only in science and mathematics, of great discoveries and achievements that were not appreciated or were even ridiculed at the outset. We in this Institution have only to recall the treatment that was meted out to Heaviside or the experiments of Marconi carried out in the face of adverse scientific opinion.

Faced with this historical background, the hapless referee is anxious not to have it on his conscience that he may have condemned a work of genius, but equally he hesitates to sanction what may prove to be a lot of nonsense. When this dilemma arises, the precaution is taken of appointing additional referees so that the final decision is at least based on a large body of representative opinion. As a general guide, if a paper presenting new concepts is written for the benefit of engineers, it should be understandable by the appropriate experts, since, if they cannot follow it, it is unlikely that anyone else will be able to do so. In other words, although it may be deemed desirable to give the author the benefit of the doubt where his conclusions are controversial or even revolutionary, he should still be expected to present his material in a logical manner so that it can be appreciated by the intended reader.

My second point concerns the overlooking of some fundamental error in a paper. I am thinking here more especially of the paper containing detailed mathematics where it is impracticable for the referee to check it line by line. Usually he relies upon the ability of the author and satisfies himself that the conclusions derived from the mathematics are sound. However, it is not unknown for a plausible answer to be wrong, while the false step in the analysis that has given rise to it may be extremely subtle.

I sometimes wonder how many published papers contain such errors that have escaped the vigilance of referees, for I must confess that in common with others I have often had to assume that the author can be relied on when his paper is otherwise in good shape. It is not unusual when glancing through scientific journals to come across corrigenda which deal, not only with printing errors, but with actual mistakes in analysis and in related numerical values. By some fortunate dispensation the authors are usually able to maintain that the error does not affect the general conclusions of the paper, but there are some notable instances where the consequences have been more serious.

It is, of course, possible to over-estimate the damage that may be done by the publication of erroneous results. Progress is often made in the understanding of a problem through the correction of errors, not only in mathematical papers, but also in the interpretation of experimental research. The human fallibility of referees may therefore have its long-term value.

Engineering Mathematics and Intuition

This discussion leads naturally to my next topic, namely the use of what I may call engineering mathematics as opposed to rigorous analysis. Coupled with this is the part played by empirical methods based on experimental results or intuitive reasoning. By 'engineering mathematics' I mean, for instance, the way engineers have of waiving the finer points of mathematical rigour. Such mathematics does not worry overmuch about existence theorems and conditions of convergence, or about the uniqueness of the solution obtained. It may sometimes depend upon the use of approximate boundary conditions needed to make a problem mathematically tractable. In many diffraction problems of the type met with in aerial design and in the prediction of television service areas, a hybrid of geometrical optics and Huyghens's principle has to be used, and theory has to be guided by experience gained from measurements.

I have already referred to the possible difference in outlook of the engineer and the professional mathematician and to the simplicity that can sometimes be achieved by making a more direct appeal to physical principles than is usual in a fully rigorous analysis. One great advantage of this method of attack is that on occasion it enables the engineer to arrive at the essential form of a solution ahead of the pure mathematician, who may, in fact, be helped by the hint which he thus gains from the engineer.

In this sense Heaviside was an engineer, although anyone who has attempted to read the three volumes of his 'Electromagnetic Theory' will know that his mathematical ability was of a very high order. T. L. Eckersley's work, also, reveals a wonderful insight into the form and physical meaning of his mathematics. It is notable that by his phase-integral method he was able to cut right across the difficulties in the derivation of the residue series from Watson's contour-integral transformation and to arrive at the esssential nature of the dependence of diffraction round the earth upon the wave frequency and the earth constants. Several years elapsed before his results were obtained by the formal extension of Watson's analysis.

The advantage of the rigorous approach is that it provides the assurance that these short-cut methods do, in fact, give the correct and complete answer, but the power of these methods lies in the simplicity with which they can often be extended to more general cases where the rigorous attack encounters great mathematical difficulties.

In the field of mixed-path propagation, including part land and part sea paths, I have acquired a certain notoriety by guessing a solution which rigorous analysis has shown to be good enough for practical purposes. In particular, I predicted a recovery effect, whereby the amplitude of a vertically polarized wave crossing a boundary from land to sea can, under the most favourable conditions, increase fourfold from the boundary out to a distance that depends directly on the wavelength. With the aid of my colleague Mr. Isted, I planned two controlled tests, one on a wavelength of about 4 m across the River Blackwater in Essex, and the other on a wavelength of about 100 m across the English Channel between Newhaven and Dieppe.

In Mr. Isted I found an ideal collaborator, not only on account of his experimental skill, but also because he was fully convinced that I was wrong. He was undeterred by my success across the Blackwater, shown in Fig. 1, which gives the result he obtained and is a monument to his integrity. Thus he set out with equal enthusiasm in the conviction that such a phenomenon could not happen across the English Channel. Indeed, when he sent me a telegram from Dieppe containing the four words, 'probably obtained expected result', I had to wait on tenter-hooks for a whole week-end until his return before I knew which way I was meant to take it.

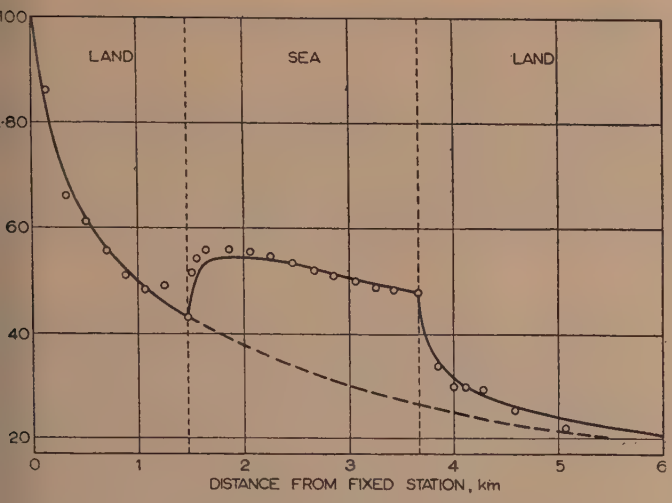


Fig. 1.—Recovery effect across the River Blackwater.

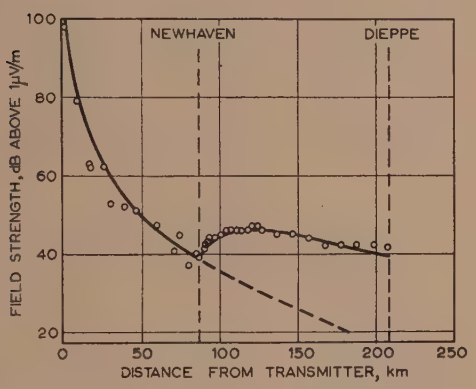


Fig. 2.—Recovery effect across the English Channel.

The answer is shown in Fig. 2, where it will be seen that no easurements were taken over the further land, though I have doubt that there would have been a rapid drop on crossing om sea to land. The curves drawn through the points in gs. 1 and 2 were actually computed by my method and are pical of the good agreement with experiment. Rigorous alysis shows that it is subject to certain errors in amplitude d phase which are nevertheless small compared with the certainties introduced by irregularities of the terrain and the mplex nature of the inhomogeneity of the earth constants. There is a warning here that, where practical applications are ncerned, we should not try to be too precise. For instance, ne of the propagation curves that have been calculated with eat accuracy from an idealized theory may give the impression t we can estimate field strengths with much greater precision n is actually feasible, and the engineer should always strive appreciate the limits of accuracy set by the practical conditions.

Notation

I turn now to the vexed question of notation, and I realize at ce that I am on dangerous ground. We all know the difficulty reading a paper, even on our own special subject, in which the tation is quite different from that with which we are familiar. one will dispute that it would make life much easier if an eed system could be universally adopted. To my mind this a counsel of perfection, and although we shall strive towards it, I see very little hope of attaining it even on a national let alone an international scale. Certainly we must avoid making it an end in itself and of creating the impression, as I am afraid is sometimes done, that a paper is not correct unless it uses some particular notation and adopts the M.K.S. system of units. We must not confuse convenience with necessity. The truth of Maxwell's equations does not depend upon the units and the notation in which they are expressed, though I am prepared to admit that, whereas I was once an unrepentant follower of Gauss, I now find it convenient to work in M.K.S. units provided that I can adjust my notation to the form I find most satisfying for the purpose.

I know of no subject in which the notation used by different authors is more diverse than in radio-wave propagation, but I have not found this a serious difficulty, even where a highly mathematical paper is concerned. If I decide that a paper is likely to be of great use to me in my work, I am prepared to study it in detail, and the mastery of a strange notation is but a comparatively small part of the job. But how can I know that the paper is of importance to me if I am not familiar with the notation, even assuming that it is well written in the sense that I have already discussed? The answer is that there is a language other than that of notation. It is the language of mathematical form.

I can probably recognize Maxwell's equations and the co-ordinate system in which they are expressed whatever the symbols used, within reason. I can see, for instance, that the solution is in terms of eigen modes and that the author makes use of Airy's equation and the W.K.B. asymptotic approximations. In such ways I can usually assess whether he is treading a well-worn track or is blazing some new and thrilling trail.

Having maintained that the meaning of the mathematics is independent of the notation in which it is clothed, I would nevertheless claim that a well-chosen notation adds elegance to a mathematical argument and may endow it with a measure of lucidity. One of our leading radio scientists, renowned for his powers of exposition, once told me that one of his papers was practically ruined by the drastic changes in notation that it suffered in the editorial stage of its publication. There is admittedly a personal element in this, but it does stress the difficulties in the way of reaching any general agreement about notation, especially in a paper which covers a wide range and contains many symbols that have to be precisely related to one another.

It is far more important to my mind to describe carefully the notation that is being used, either in a special list at the beginning of the paper or as the symbols occur. One danger of using a conventional notation is that it may be taken too much for granted by the author, so that the reader who is not familiar with it may be left guessing and have to spend a considerable time sorting it out from the context, especially when he wishes to make use of numerical results.

Statistics and Specific Situations

I pass on now to some thoughts on the use of statistical methods. The few remarks I wish to make concern the use of statistical results when dealing with specific situations, and I will illustrate my meaning from the consideration of television service areas. In this connection, field strengths are often expressed in terms of the average value that will be obtained at a given percentage of locations for a given percentage of the time. Except in the fringe areas, the temporal variations due to changing meteorological conditions are usually small, but the field strength at a given distance from the transmitter may vary greatly from place to place on account of ground irregularities and man-made obstacles.

It may be argued that, as a result of a measurement survey or of a prediction based on a study of ground profiles, a certain field strength will be obtained at 50% of locations on a circle of given radius round the transmitter. This may be the best scientific way of assessing the problem in general, if it is proposed, for instance, to provide curves and data for the guidance of engineers who have to take an overall view of television planning. But when it comes to the serving of a particular area where the terrain may be exceptionally rugged, or of a particular town that is unfavourably placed, this general picture may be inadequate.

It is scarcely fair to suppose that the population within a service area is uniformly distributed, and it may matter very much that a given town is not, in fact, so well served as other towns at the same distance from the transmitter. On the other hand, it may be desirable to express the figure for the town itself statistically with respect to various locations within it and to assume an even distribution of population, though in special cases account must be taken of local topography when trying to anticipate possible black spots in shielded areas. There will always be the unfortunate people to whom it is small comfort to be told that 99% of the people in their neighbourhood receive an excellent picture.

The problem arises rather similarly with respect to temporal variations in the preparation of tropospheric propagation curves showing the field strength from a given transmitter that will be exceeded for various percentages of the time at distances that are well non-optical. Such curves are of great importance to the C.C.I.R. in connection with the spacing of television stations and fixed relay links sharing the same frequencies. These curves are drawn through a spread of points, each one of which represents a time average at a given location for a specific link. This means that, for a point that lies a long way off the curve, the performance over the circuit to which it corresponds will on the average differ considerably from the value given by the curve at the same distance. I wish, therefore, to plead that in applying statistical methods we should keep a sense of perspective.

I do not mean in any way to decry statistical analysis where the use that is made of the results takes due account of their statistical nature. If, for instance, the performance of a projected radio link is quoted in terms of a percentage time reliability derived from a long series of fading records, then the acceptance of the link carries with it an acknowledgment that any temporary failure that is within the limits of the specification can only be defined statistically. I can recall a case in which the proposal of a radio link with a very high predicted performance was rejected because an essential condition was that it should not fail on a particular afternoon of special importance to the users. Actually the limit imposed by the propagation medium was not much worse than might be attributed to maintenance hazards.

The chief difficulty in applying statistical methods arises when the basic material is very complex. The factors determining ionospheric weather are complicated. Great advances are being made in the methods of predicting maximum usable frequencies, but many problems remain with regard to the effect of the solar cycle and the occurrence of ionospheric storms. The attempts that are being made to give storm warnings have met with some limited success, but it is still a matter of debate whether it is more disturbing to take elaborate precautions against poor transmission conditions that do not materialize than to suffer the dislocation to traffic caused by ionospheric storms whenever they happen to occur.

Much work has been done by correlation and cycle-matching

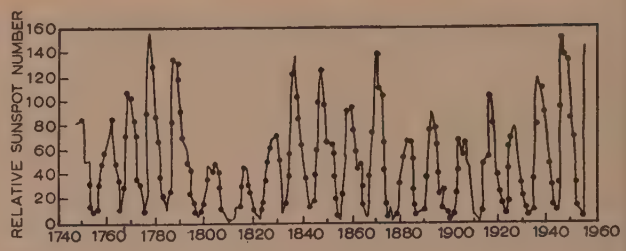


Fig. 3.—Record of solar activity.

techniques to predict the future trend of the sunspot cycle, bu Fig. 3, showing the sunspot numbers since they were firs recorded in 1749, indicates how limited is the material in relatio to its complexity. It has been suggested that the recent excep tionally high solar activity may be followed by several cycles o low maximum activity, by analogy with the trend of the cycles i the early part of the record. Such a possibility may have grea implications with regard to frequency allocations during the nex 50 years, particularly in relation to ionospheric forward-scatte circuits and the planning of high-frequency communication.

It is obvious, however, that this may be mere wishful thinkin as the sample available of the long-term cycle of 170 yea implied in the suggestion is too small for such conclusions to b confidently drawn. This is, in fact, an example in a broade sense of the attempt to be too specific in the application o statistical data, which has been the main theme of thi discussion.

Speculative Reasoning

My concluding thoughts concern an activity in which I onl indulge, if at all, with great diffidence. It is the use of highl speculative reasoning to build up an elaborate theory. Lor Rutherford once twitted one of his friends with being able t reconstruct a whole brontosaurus from one thigh bone and fift barrels of plaster of Paris, but he was himself renowned for h ability to see the significance of observations that would hav escaped the notice of more ordinary men.

I feel very humble when I try to read the many papers tha are appearing on the constitution of the atmosphere and on th physical processes governing the formation of the ionospher layers revealed by radio sounding and rocket exploration; bu when I have been carried away by the daring argument in on paper, I find some solace for my inability to think such thing when I come across another in which the author proves co clusively that the previous one was completely wrong, because took no account of some incontrovertible fact. Not many yea ago most people believed in the formation of the solar system a brilliantly described by Jeans. It seemed so obviously true an explained so much. But to-day we are confronted with quite different story put forward with equal vigour—and as obv ously true.

Lest I should appear to be derogatory, let me hasten to explai in all sincerity that I have the highest admiration for the autho of these flights of the imagination. It is thus that true progre is made, for they are rare spirits who venture into the unknow and bring back strange stories of what they have seen. Gradual the picture takes shape, even though some of the pieces of th puzzle may at first be ill-defined and be fitted into the wron places. In this process our arts of radio and telecommunicatio will assuredly help in resolving the true shapes of some of th pieces.

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MEASUREMENT AND CONTROL SECTION: CHAIRMAN'S ADDRESS

By J. K. WEBB, M.Sc.(Eng.), B.Sc.Tech., Member.

'THE SCOPE OF THE MEASUREMENT AND CONTROL SECTION'

(ABSTRACT *of Address delivered 14th October*, 1958.)

To be elected your Chairman is a distinction and I accept it with both pride and humility. I am deeply appreciative of this honour, which I feel is a very generous compliment, not only to me personally, but also to the great international telecommunication organization which I have been proud to serve during the past 34 years. During my term of office, I shall always strive to maintain the high standard of service set by my predecessors.

I propose to talk this evening about a number of subjects which come within the purview of our Section as it is now constituted, in order to illustrate its present scope, and I shall approach the task as one who has enjoyed a fairly long and varied career as an electrical engineer engaged in industrial research and development, besides several years' experience as a part-time lecturer.

The scope of the Measurement and Control Section has been greatly extended since its early days, and although it has never lagged in its concern for the more fundamental measuring devices, the impact of improved analytical methods, the continuous urge towards ever greater precision in the definition of our standards, the advent of new materials, nucleonics and improved measuring techniques, computers, data-processing and servo mechanisms, have all added to the complexity of its interests.

It is convenient to divide the work of the Section into five main 'panels', and I propose to give the heading of each in turn and then to indicate its scope by briefly discoursing on one or more relevant items.

Panel 1: Fundamentals, Standards and Laboratory Measurements

This panel includes notations and theorems besides the practical means of constructing and calibrating standards.

Let us first consider the question of notation, which is perhaps one of the most fundamental things in electrical engineering and concerns, amongst other things, our choice and representation of units. This subject may seem rather remote to many of you, but just reflect on what life would be like if we were obliged to do our sums in Roman numerals. Arabic notation, you must admit, has saved us much unnecessary thought. Now, as it happens, we have all suffered, perhaps without realizing it, from having been brought up on an ill-conceived notation, comprising a practical hotch-potch of modified unrationalized C.G.S. units with their unfortunate duality of electrostatic and electromagnetic forms stuck uncomfortably together, and with 4π's popping up in all sorts of odd places without any obvious relation to the geometry of the problem. It is a wonder that anyone is expected to think rationally in the framework of such a jerry-built and creaking edifice.

There is, happily enough, a very easy way out of this difficulty if we only have the courage to take it. That is, wholeheartedly to adopt the rationalized M.K.S. system of electrical units, not as just another system, but as one which we should use exclusively. This would result in a marked simplification of practical calculations and of the study of electrical theory in schools, besides saving much time and intellectual fatigue.

Conscious of its responsibilities in this matter, The Institution sponsored a symposium of papers on the M.K.S. system in 1950,[1] which provided an opportunity of presenting and discussing relevant technical matters. From this symposium it became abundantly clear that the universal adoption of the M.K.S. system would be eminently desirable.

Such also became the opinion of the Council, since in 1952[2] they adopted a resolution encouraging the use of the M.K.S. system, but still allowing authors freedom to use the C.G.S. system. I suggest that the time is now ripe for a stiffening of this resolution by making mandatory the use of the M.K.S. system in the *Proceedings*. This would, I believe, have two effects. First, by obliging members to take stock of the practical working of the M.K.S. system, it would remove many of the misconceptions which at present exist, and secondly, it would probably have a snowball effect on the attitude of other authorities.

Passing now to the consideration of electrical standards, we quite naturally associate this subject with the National Physical Laboratory. As an introduction, there are two excellent progress reviews published in the *Proceedings* in 1942[4] and 1952[5] by one of our Past Chairmen, Dr. L. Hartshorn, whose name is closely connected with that Laboratory. All electrical standards are ultimately referred to mass, length and time, and progress is still being made in defining these parameters. The precision with which mass can be defined has increased following recent developments in weighing techniques and is now about 1 part in 10^9, which is equivalent to 1 oz in 28 000 tons. Measurement of length which, for the past 75 years, has been made in terms of the platinum-iridium bar housed at Sèvres, will be made 100 times more accurate this year by the adoption of the wavelength of a particular orange line in the visible spectrum of an isotope of krypton, and will be definable to about 1·5 parts in 10^8, or 1 inch in 1 000 miles. Time and frequency, first measured in terms of the earth's rotation, then with crystal standards, and now in terms of molecular resonance, has yielded an increasing precision and now stands at about 3 parts in 10^{11}, or getting on for 1 second in 1 000 years. Such quests for greater precision are not purely academic, but are usually backed by very practical considerations, as, for example, problems in telecommunication and navigation.

Considerable ingenuity has been exercised in referring our electrical standards to the primary standards of mass, length and time. Thus the ampere is referred to mass by means of the Ayrton–Jones current balance, the ohm to length and time by Albert Campbell's bridge method and the henry to length by the Campbell standard of mutual inductance.

The determination of the farad has presented some anomalies in so far as it has always remained a secondary, derived unit, being measured in terms of mutual inductance and resistance by the Astbury–Ford modification of the Carey–Foster bridge.[6] This is rather a long way round, with inevitable loss of accuracy,

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and it is not surprising that experimenters have wistfully regarded the possibility of measuring the farad directly in terms of length.

A practical way of doing this has recently been suggested following the publication in the *Proceedings* of a very interesting theorem by Lampard,[7] for which he was awarded the Heaviside Premium. His theorem can best be grasped by considering a square cylinder constructed from four conducting plates which are insulated from each other at the corners as in Fig. 1.

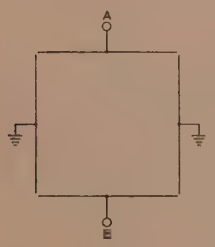


Fig. 1.—Square cylindrical capacitor which has constant direct capacitance per unit length independent of its size.

Lampard first showed that the direct capacitance between points A and B (neglecting corrections due to finite gaps) has a constant value per unit length independent of the size of the square. He then demonstrated that the same constant value was to be obtained from other configurations, limited only by the requirements that the cross-section have one axis of symmetry and that it be a closed curve. The capacitance of such a configuration is unfortunately rather small, being only about 1 pF per 20 inches, but it is completely defined in terms of a single measurement of length.

A configuration due to Thompson (mentioned in Lampard's paper), which has important advantages from the constructional viewpoint and which also minimizes the disturbing effect of the finite gaps, is shown in Fig. 2.

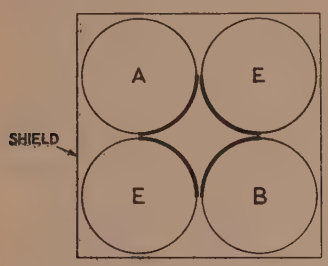


Fig. 2.—Thompson's capacitor standard, based on Lampard's theorem.

The four cylinders with which this capacitor is constructed can readily be machined with great precision. The direct capacitance between opposite cylinders such as A and B is, moreover, highly insensitive to the width of the gaps, tucked away, as they are, in re-entrant positions. End guards define the effective length of the rods.

This configuration, which takes the form of a 3-terminal capacitor, presents an interesting measurement problem, since the direct capacitance, which is only of the order of 1 pF, has to be determined with negligible error (say to about 1 part in 10^6 or to 1 μpF) in the presence of very much larger values of guard-ring capacitance. The outcome of this proposed system of measurement will be awaited with much interest.

Panel 2: Materials and Components

Leaving standards, we now pass to quite a different field of activity. Every year there appears some material which is particularly topical and which engenders a spate of technical literature as its characteristics and potentialities are explored. Such is now happening in the case of silicon, and only, be it noted, following the advancement of measurement techniques. Semiconductors have come more and more into the limelight since selenium was first used about 1927 in the manufacture of power rectifiers. It was not until 1948, however, that semiconductors really came into their own with the invention of the transistor. Germanium was then the favoured material, but despite its otherwise excellent characteristics, it has one disadvantage in so far as it cannot be operated at much above room temperature. Attention has therefore been focused on silicon, since it does not suffer from this limitation. Silicon exists plentifully in nature in the form of its very stable dioxide, silica. It is, however, a singularly difficult element to isolate in the very high degree of purity required for making transistors. Although a grade 99·95% pure had been produced during the Second World War and was used for making crystal mixers, such silicon is still far too impure for making transistors. Many workers therefore concentrated on the production of a more suitable 'hyper-pure' silicon, and about 1948 such a grade became available. A typical example was that made by the so-called du Pont process, which involves the vapour phase reduction of silicon tetrachloride with zinc at about 950° C in a fused-quartz apparatus.

The evaluation of the quality of such silicon is a big subject by itself, since the most sensitive chemical and physical tests, including mass spectrometry and activation analysis, are of little avail. We therefore become almost entirely dependent on electrical measurements made on monocrystals, but it is nevertheless astonishing how, from measurements which are basically simple, but which yet require great skill and care in their performance, it is possible not only to determine impurity levels down to such fantastically low values as 1 part in 10^{12} (which is equivalent to a single grain in 1 000 cubic yards of sand), but to designate the various elements contributing to this impurity. The measurements in question are simply those of resistivity and Hall effect at various temperatures.[9]

The relationship between resistivity and impurity concentration at room temperature, deduced from physical theory and supplemented by measurements, is shown in Fig. 3.

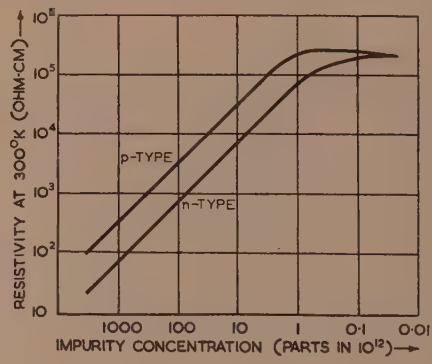


Fig. 3.—Curves which enable the impurity concentration in silicon to be determined from measurements of its resistivity.

The assumed mobilities are
μ_n = 1 700 cm²/volt-sec.
μ_p = 400 cm²/volt-sec.

From this it is seen that the resistivity of intrinsic silicon at room temperature is about 230 000 ohm-cm. It is not necessary to go to such extremes as this, however, even if it were possible, the practical aim being to produce a silicon of resistivity higher than 1 000 ohm-cm.

The more troublesome residual contaminant is boron, which cannot be removed by zone-refining methods; its effect is to produce a *p*-type material. Since there are invariably other

mpurities present, the precise contribution of the boron by tself is usually unknown, and hence the material is of dubious uality. Moreover, to produce a satisfactory *n*-type material t is essential virtually to eliminate the boron. The trouble with ilicon produced by the zinc reduction method is that, even after one refining, there is still enough boron and other contaminants resent to keep the resistivity down to about 100 ohm-cm.

To devise the means of producing a virtually boron-free ilicon of resistivity greater than 1 000 ohm-cm has been a major ndertaking and has involved considerable development effort. am therefore happy to pay tribute to my colleagues, who by heir genius and team spirit have succeeded in evolving a practical ngineering solution to this most difficult problem.[8]

From the philosophy that it is generally easier to purify a gas han a solid, they first produced a gaseous silicon compound, ilane, or silicon hydride, which, after extreme purification, was ecomposed to form silicon and hydrogen. It was then con- erted into monocrystal form by a process which did not involve isk of contamination from crucibles. Much ingenuity, including he use of such effects as magnetic levitation, has made this ossible.

The device maker usually requires a comparatively low- esistivity silicon, which can only be effectively obtained by loping the original high-resistivity material with precise quan- ities of elements which are themselves of comparable purity. Thus, to produce good-quality *p*-type silicon, the additive may e diborane, and for *n*-type, phosphine, both of which are of he same order of purity as the original undoped silicon. The ilane process, moreover, enables such additives to be uniformly lispersed, since they can be readily mixed in during the gaseous tage.

In conclusion, it is fair to say that we, in this country, have een first to produce, on a commercial scale, 1 000 ohm-cm ilicon with a hole lifetime above 200 microsec for *p*-type naterial, and, now that it is available, many important develop- nents in the transistor field should follow.

Panel 3: Measuring Techniques, Devices and Instruments

In this panel we have a wide and flexible choice of subject anging from nucleonics to transistors. This must therefore be ny excuse for deviating slightly from the beaten track and aying something about recent developments with which I have een involved and which have great practical significance. They oncern means of securing good electrical connections, a subject f interest to those engaged in such diverse fields as power ables, domestic wiring, telecommunication, computers and lectronic apparatus. In the present context, however, dis- ussion will be limited to the connection of copper conductors f cross-section equivalent to that of a wire of approximately ·020 in diameter, or No. 25 s.w.g.

From the very earliest days of the electrical industry, the oldered joint has been regarded as the best and most permanent neans of connecting copper conductors together, and if well nade by a skilled operator, it can still be recommended with onfidence. Skilled operators, however, are nowadays at a remium, and so, with the number of permanent connections nade annually reaching astronomical figures, we can no longer ely upon every soldered joint having been made with all the ttention which it merits. For this reason the defective, dry oldered joint has become more and more of a menace, causing ndless trouble and inconvenience in manufacture and service.

The advent of the printed circuit eliminated the necessity of naking certain types of joint individually by hand, and hence lso the human element. In this scheme, all joints can be oldered automatically by dipping them in a trough of molten older. The initial deficiencies and vagaries which accompanied this process had the good effect of directing attention to the technique of soldering, which, in this case, lends itself to close control. Considerable improvements have consequently resulted which lend certainty to the operation.

Printed wiring, however, has a limited application and cannot readily be applied to such problems as making connections to relays in telephone exchanges. The deficiencies of the hand-made soldered connection therefore prompted the Bell Laboratories to investigate alternative types of connection, and in 1953 the first of a series of papers appeared under the general title of 'Solderless Wrapped Connections'.[10] There is, of course, nothing new in making a connection by twisting the wires together or in wrapping a wire around a terminal post. What *is* new is the exact way in which it is carried out, including the tool which makes the connection, together with the means employed to secure large contact area, high contact pressure, the storage of sufficient elastic energy to ensure at least 40 years' trouble-free service, and compactness.

The surprising thing is that such a wrapped connection not only equals but surpasses an equivalent soldered connection made by a skilled operator. Having once proved that, we can afford to dwell on its many other advantages, in particular its certainty, reliability, low cost, compactness and the ease with which it can be made with the ingenious specially designed wrapping tools now available.

This is a development which we were not slow to examine closely on this side of the Atlantic, and we have lost no time in absorbing the Bell Laboratories' technique and in carefully checking their findings. Naturally we have also sought improvements, and I would draw particular attention to one variation which we have developed and which may result in greater flexibility in certain instances than that originally envisaged. The Bell Laboratories have concentrated on what has been termed 'primary wrapping', or otherwise simply the *wrapped* connection; i.e. in connecting, say, a resistor to a terminal post, it is the actual resistor lead which is wrapped around the post. An alternative method, however, is to lay the resistor lead beside the terminal and bind both together with a separate piece of wire. This has been termed 'secondary wrapping', but is perhaps better described as the *bound* connection. Both types are illustrated in Fig. 4. It has been found that binding can give an

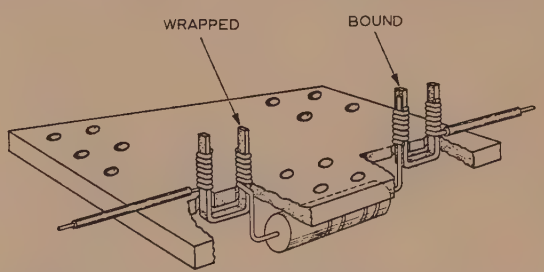


Fig. 4.—Sketch to illustrate the distinction between wrapped and bound connections.
Outer interconnecting wires are wrapped in both cases.

equally good connection and has certain advantages. The same size of binding wire may invariably be used and fed from a magazine power-driven wrapping tool. The optimum type of binding wire can be used. Such connections can be undone and remade repeatedly without damage to the component lead. Doubtless, however, both the wrapping and the binding methods will in time find their best spheres of application.

How to test a wrapped or bound connection to ensure that it would have a life expectancy of at least 40 years under all the adverse conditions it is likely to encounter has been a major

problem. As is well known, an accelerated test is not always convincing proof, but fortunately we have at least 10 years' field experience already available with less favourable types of solderless pressure connections, and this, together with the results of very severe accelerated ageing tests, has given sufficient confidence to warrant full-scale field trials. The ageing test includes resistance measurements before and after severe heat cycling, vibration, exposure to various humid and acid atmospheres, etc.

From the results of these tests, and from field experience, it has become evident that the wrapped or bound connection has much to commend it over the equivalent soldered connection and has effectively eliminated the dry-joint menace. Like all great inventions it has the supreme merit of simplicity, and is likely to play a very big part in future wiring problems.

Panel 4: Data Processing, including Analogue and Digital Computers

Referring in particular to the automatic digital computer operating at electronic speeds, this is a very recent innovation and one which is certain to have far-reaching repercussions as it comes more and more to insinuate itself into the conduct of our technological and business affairs. Already it has been successfully applied to scientific computations, to business accounting problems and to the control of machine tools.

The Section has a great responsibility in furthering the associated engineering problems, and this it has endeavoured to do by actively encouraging the presentation of technical papers which appear in the *Proceedings*. To cope better with the rapid rate of progress of the subject, however, the Section has also now instituted a new kind of forum taking the form of Specialist Discussion Meetings, which it is proposed to hold biannually, at which material, addressed essentially to specialists, can be presented and freely discussed with the minimum formality. The first of these meetings is planned for February, 1959, and details have already been published in the August issue of the *Journal*. It is envisaged that such discussions, together with the personal contacts which they promote, will stimulate ideas which can later be written up as formal papers.

Thus, by way of example, one session of the forthcoming meetings is to be devoted to low-temperature devices for storage and switching, and perhaps, without prejudice to what is to come, I may now say a few words about the very interesting topic of storage which is at present in such a rapid state of development.

A vital component of any digital computer is the memory, or store, into which intelligence can be inserted and from which it can subsequently be withdrawn. Up till about 1940, when the idea of applying electronics to computers was first mooted, the punched card served this function, but to cope with electronic speeds it became necessary to replace it with something much faster. Since then, practically every effect known to science which can be said to possess a 'memory', even including some unlikely ones such as thixotropy, and more esoteric ones such as spin echoes based on nuclear induction, have been and are still being diligently explored, and their relative advantages carefully weighed in relation to the problem in hand. Besides such general questions as reliability, ease of maintenance, the nature of the ancillary equipment, permanence, temperature dependence, volume, etc., the two most important questions to consider in assessing the merits of any memory system are access time (the time required to transfer information from the memory unit through the associated circuitry to the point of need), and economic factors including capital and operating costs.

Typical of those devices out of the many explored which have so far come out on top are magnetic tape, magnetic drums, magnetic elements and now, the latest, superconducting elements. The access time associated with these devices is indicated in Table 1.

Table 1

Typical component	Order of access time
	sec
Magnetic tape	10
Magnetic drum	10^{-2}
Magnetic elements	10^{-5}
Low temperature devices ..	10^{-8}

All such devices can store digits by virtue of the remanent magnetism which results from the application of a magnetizing force greater than a certain critical value. The relatively low cost of the magnetic drum, combined with large capacity and an access time which is short enough for many applications, explains its popularity.

One way of constructing a store of magnetic elements is to use tiny ferrite cores which must first be individually checked and then threaded with appropriate windings. The matrix, comprising a number of such cores assembled to form a co-ordinate array, is a typical example. At least two co-ordinate wires, an inhibit wire and usually a fourth 'reading' wire must be threaded through each core, and, with the desirability of making the cores as small as possible, this is not an operation which lends itself too easily to large-scale manufacture, taking a megabit store as a basis of reference (which is the size necessary to store the information of a small 30 000-word novel). Alternative methods include forming the elements by means of ferrite wafers perforated with holes,[13] the ferrite in the immediate vicinity of each hole serving the same function as a discrete core, or else the use of deposited thin films of magnetic alloy. The capital cost of such stores is at present about 20 times that of magnetic drums of the same capacity, so that they tend to be limited to small buffer stores used in conjunction with the latter.

A recent and novel variant on storage in magnetic elements is the Bell Laboratories' Twistor,[11] which, by replacing ferrite cores with straight magnetic wires, would seem to facilitate large-scale production. The device depends upon a curious phenomenon that, if a magnetic wire is twisted, magnetization will prefer to be along a helical rather than a longitudinal path. Its development will be awaited with interest.

There are other variants, including 'window'-type elements[12] designed to increase the switching speed, but these are more elaborate in so far as they have to be provided with supplementary windings to provide bias.

Anyone who undertakes such development work must always be distracted by the necessity of constantly looking over his shoulder to see how likely he is to be overtaken by some alternative scheme. For a time there was competition from cathode-ray tubes and ferroelectrics, but at present they do not appear to be in the running, although some fresh development may completely change the situation. The latest challenge, however, has come from a rather unexpected source—low-temperature devices.

The phenomenon of superconductivity in various metals at temperatures below about 10° K was discovered in 1911, but it never assumed engineering significance until helium liquefiers or 'cryostats' became commercially available in 1954, and an account appeared in 1956 of a superconductive computer component called the Cryotron.[14] This is a new circuit-element having power gain and current gain which can be used in flip-flop circuits, gates, counters and other computer circuits. In

957 a memory cell based on flux trapped in superconductors y the application of a magnetic force above a certain critical alue pointed the way to the design of a large memory having a ycle time of only 10^{-8} sec.[15,16] This very fast switching speed of great interest to computer designers. Machines are now eing designed to perform about a million arithmetical opera- ons per second, and arithmetical circuits and stores act as each ther's pace makers. It is too early even to hazard a guess at the apital and operating cost of such a store. Perhaps we shall arn more about it at the discussion next February.

Panel 5: Servo-Mechanisms and Control Systems

There has been much talk recently about automation, which, n the more popular sense, may be said to be an attitude of nind that is always seeking to decrease the labour content of ny series of jobs. Although servo mechanisms are at the heart f automation, as engineers we are chiefly concerned with nother more technical aspect, that of achieving by their means esults which, by human agency alone, are very difficult, if not mpossible. The whole subject has many ramifications some of vhich I can safely leave to our Vice-Chairman, Professor Tustin, vhose recent contribution to the *Proceedings* will be published n November.[17]

For the present I shall simply endeavour to entertain you by irecting your attention to some work carried out by D. A. immons[19] of the British Scientific Instrument Research Associa- ion and made available to me through the courtesy of one of ur committee members, Dr. A. J. Maddock, whose excellent eview of 'Servo-Operated Recording Instruments' was recently ublished in the *Proceedings*.[18]

The subject—that of magnetic levitation—is one which has ascinated me for some time, and whilst at present much of it is till a curiosity, I cannot help feeling that important practical pplications may evolve, just as they have in the case of super- onductivity.

Everyone must have observed the eagerness with which a eeper will leap up and engage with a permanent magnet once ravity has been overcome. With a piece of iron and a cored lectromagnet, a similar thing happens as soon as the latter is ufficiently energized. To those unfamiliar with servo mechanisms t might seem incredible that they enable the force of gravity and he force of magnetic attraction to be so nicely balanced that the ron can be levitated and held quite stationary in mid-air, yet his is so.

As the iron approaches the core of the electromagnet it inter- epts a beam of light which falls on a photocell. This controls he current in the coil of the electromagnet, and this current ccordingly varies as the iron is displaced from a predetermined evel. Whenever the iron tends to fall to earth, the current is ncreased and gravity is overcome, and vice versa. From this t is seen that there is a tendency for the iron to oscillate up and lown, and here we come to a most important feature of any ervo-mechanism system, that of damping out such oscillations. To do this it is necessary to arrange for the current in the coil o vary by an amount proportional not only to the displacement f the iron but also to the rate of change of this displacement. By adjusting the value of this so-called derivative control and ompensating for any phase lag between effect and cause (in this ase the current in the coil and the movement of the iron), irtually complete damping can be achieved.

It has been suggested that the scheme discussed could be pplied to automatic weighing techniques, which may very well e so, but at all events I think you must agree it does very aptly llustrate the sort of thing which can now be done with the aid f servo mechanisms.

Conclusion and Acknowledgment

Many Institution members are perhaps a little hazy about the scope of the Specialized Sections. I have tried to enlighten them, at least as far as the Measurement and Control Section is concerned, by touching very lightly on just a few topics, picked almost at random, which have interested me personally, and which are published by kind permission of Standard Telecommunication Laboratories Limited. These may serve to indicate, however imperfectly, the wide range of subjects which now come within the Section's purview and, I trust, persuade members to participate more fully in its work.

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CENTRE, SUB-CENTRE AND GROUP CHAIRMEN'S ADDRESSES

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NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By Professor F. C. WILLIAMS, O.B.E., D.Sc., D.Phil., F.R.S., Member.

'REMARKS ON RESEARCH'

(ABSTRACT *of Address delivered at* MANCHESTER *7th October*, 1958.)

The past 25 years has witnessed a revolution in the utilization of mechanisms of all kinds to provide a continually improving standard of life for the community as a whole. The revolution has been particularly dramatic in the field of electrical engineering. The use of mechanisms is not only augmenting and largely replacing the physical labour aspect of human work; it is also, through the computer and its derivatives, augmenting and in some respects replacing the mental labours of the human brain.

This continuing increase in the availability and use of mechanisms presents many problems, both in general terms and in particular with relation to university education. Taking 'use' first, the implications of this aspect are obvious and have been frequently stated. If there are to be more mechanisms in use, there must be more scientists, technologists and technicians to manufacture and service them. Hence, of course, the current urge to expand the universities and technical colleges.

Increasing availability of mechanisms has two aspects—more of the same thing as before, and new things. New things appear so consistently that it is all too easy to assume that continued progress, and a continually improving standard of life, are part of the natural order of things. They are not. Progress requires that someone, somewhere, should do or make something that no one has done or made before. It may be a small thing or it may be very big, but, whichever it is, it is an exercise in originality. These various activities are covered by the broad title 'research', as it is used in academic circles, and it is in this sense that the term will be used here. In the world outside, research also includes at least one other activity, which may briefly be described as 'pulling the sales department's chestnuts out of the fire', an operation which is undertaken with some urgency when a sales department has sold something that the factory cannot yet produce. This activity is excluded from my definition, because research as I understand it, and as I have seen it in action in such places as T.R.E. during the war, is a driving force and guiding star, and not a straw to be clutched at by a drowning man.

Scientific research covers a very wide range all the way from purely theoretical extensions of higher mathematics to almost purely experimental investigation of properties of materials so complex in their structure as to be almost beyond the reach of theoretical investigation. Though the engineer is free to operate anywhere in the range, his natural home is towards the latter end, where he is firmly caught between the upper millstone of the laws of nature and the lower millstone of the properties of materials.

In this range pure science, essential though it is, is not enough. It must be allied with art, experience and a certain amount of low cunning. It is here that what I will call 'inventive research' has a major place; it spreads all the way from small design improvements to complex new devices or systems, such as jet engines, nuclear power stations and computing machines.

Every mechanism that currently aids our daily life springs from some basic invention in the past and subsequent more or less inventive improvements. Anything significantly new in mechanical aids in the future, and the continued improvement of existing ones, will require continuing inventiveness from someone.

Experience suggests that inventiveness is rare. There is a world of difference between learning how to do something that someone else can teach you, and discovering how to do something that no one else can teach you to do. The disparity is even greater if no one can even tell you what the something is.

This is because once a thing is known, or exists, it has so many links with pre-existing knowledge that it can be made to appear as a logical extension of that knowledge, but the probability is that the extension has been arrived at through only one link with the past, and that not the shortest.

Again, it is relatively easy to train a student to pass a particular examination, provided that the syllabus is pre-ordained and that there is available an adequate case history on the type of question the examiners are likely to set. The process is known as 'cramming', and properly done can produce from the student results which bear no relation at all to his real ability and most certainly no relation to his inventive capacity. The narrower the front the greater is the disparity. It is, however, a very different story if one considers how to train people to do things that have not been done before. Cramming is obviously impossible, the teacher himself does not know what in due course the student will originate.

It is a prime requirement of the educational system that it shall produce a continuing supply of people capable of original work. Such people are of particular importance to this country in its competitive struggle for economic survival, because ideas, suitably embodied in hardware, or suitably protected by patent law, are exportable. On the other hand, the raw material consumed in having an idea is negligible; the incremental fuel cost of intense mental effort has been estimated at one peanut per hour.

This, then, is the general background. It is a situation which obviously presents many problems to the university engineering departments, some of which have already been touched upon. The remainder of these remarks will be devoted to discussing the role of university research groups in this situation.

A research group is made up of a number of teams each comprising teaching staff, post-graduate students of all grades and technical assistants, each team being devoted to a different aspect of electrical engineering but housed in the same building as the undergraduates and open at all times to their casual inspection.

It might appear at first sight that a deep involvement in

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earch by a member of the staff would detract from his value a teacher by draining off a good deal of his energy and time. closer investigation the reverse is easily seen to be true. teacher may teach for, say, 40 years, during which period subject will expand enormously. It is far better for him to ep up to date by being deeply engaged in the process of self- ıcation by research than to attempt to do it purely as an act duty.

A teacher is much more likely to infect his students with husiasm if he himself is so convinced of the importance and erest of his topic that he is prepared to spend most of his king hours worrying about it. Furthermore, a teacher gaged in research is apt to be thrown back again and again fundamentals in trying to solve his own problems. He is refore more likely to emphasize fundamentals in his teaching. From the viewpoint of the student the most frightening ect of the situation is the continued expansion of the scope electrical engineering.

A complete solution to this problem can never be found by ension of courses or the skilful rearrangement of their content. en if time allowed it, such a course of action could only epare him for the world as it is, not as it will be during the odd years of his working life.

Much of what he later needs to know he will have to find out himself, and a keen inquiring mind, coupled with the ability apply fundamental knowledge to new situations, is far more uable to him than any amount of specialized technical owledge. In the development of these attributes the spirit t animates the teaching and the general atmosphere in which s conducted are far more important than the content of the ırse. The teacher is in fact more important than the topic, d as has been indicated, research activity can help to produce e right type of teacher and to provide stimulating surroundings. Again, the 'men of ideas' of the future will largely spring from ong these students, which poses the question, How can ople be taught to have ideas? The simple answer is, of course, t it cannot be done. All that can be done is to select people h natural ability and encourage them, by exposing them to environment in which original ideas are regarded as important ngs, for which credit and standing and advancement can be tained. Originality, like measles, is contagious, but again e measles, it will only be caught by those susceptible to it.

The development of originality is made difficult at under- duate level by the examination problem, and the difficulty aggravated if the examinations are set externally on a pre- lained syllabus. Inevitably the chief concern of the student is pass the examination, and since the answers to questions set a fixed syllabus are known, the student's best bet is to learn se answers rather than attempt an original solution, for ginality and certainy can never go hand in hand. Even so, a nulating teacher teaching in his own field of interest, and given free a choice of his subject-matter as circumstances will allow, ı do a great deal.

t is, however, at the post-graduate level that a flair for ginality can be given its first real chance, by associating the dent with some research activity, and by replacing the mination bogey by the requirement that he shall be able to nonstrate, by writing a thesis, that he has a grasp of the entials of some unsolved problem, and has applied his talents assisting in its solution. He is brought up sharply against fact that he will not always be able to get the solution to his iculties by asking someone to tell him the answer, or by dying a textbook. What he has learnt ceases to be something needed to know to satisfy examiners, and begins to be forged o a tool with which he can lever out new information for nself.

There are, of course, many places outside the universities where post-graduate training in research can be obtained, but one great advantage of university research is that activity is not confined to a particular sphere, nor is it necessarily directed towards a fixed objective. It is free to take the line of least resistance and to exploit any break-through, no matter where it may lead.

Thus, a strong research school with several different lines of interest is not only necessary to provide facilities for the post-graduate student to develop his talents, it can also exert a beneficial effect on the undergraduate school on both sides of the lecture bench. In addition, of course, there is always a chance that something really useful will come out of the work. The chance of something useful emerging and of being actually used is greatly increased if close and informal links can be formed with industry, preferably local industry. Collaboration in research effort is probably the best way of maintaining and expanding the close contact with industry that is so important to the future of engineering education.

To summarize: university research in engineering can provide valuable contributions in at least five ways:

(i) By extending the boundaries of knowledge.
(ii) By keeping the staff lively and up to date in their own speciality.
(iii) By demonstrating to the student the dynamic nature of the subject and encouraging a flexible approach to it.
(iv) By providing an atmosphere in which the student can develop any talent he may have for original work.
(v) By tightening the links between industry and the universities and increasing their mutual understanding.

The first objective is well known; the others may be less widely appreciated, outside academic circles, and yet they may be more important in the long run, because the boundaries of knowledge, particularly in engineering, can be, and are, subject to continual expansion outside the universities. Furthermore, much of this expansion can only take place outside the universities because of its scale or its direct application to production. It is therefore important at all times to ensure that contribution (i) does not predominate; the project must not assume overriding importance at the expense of its usefulness as a vehicle of education. For similar reasons, the development of a separately staffed post-graduate research school, though it may accelerate the extension of the boundaries of knowledge, is almost certain to do so at the expense of the stimulation of undergraduate teaching.

From the point of view of the indirect benefits of research, (ii)–(v), the importance and success, or otherwise, of the work undertaken is not a prime consideration, but there is, of course, nothing quite like a resounding success to heighten morale.

By way of conclusion, two examples will serve to illustrate these and other aspects of university research.

The Electrical Engineering Department at Manchester contains what is probably the most potent computing organization in any university in this country. It provides a nation-wide computing service covering a very wide field of interest, mainly far removed from electrical engineering.

If the history of this apparently illogical but highly successful development is traced back, it is found to depend, not on any deliberate preplanned policy, but on a series of fortunate accidents coupled with freedom to pursue what appeared to be the most profitable course at any particular time without paying too much attention to where this might ultimately lead. Thus, the original impetus came from work on storage systems, during which a particular, somewhat fortuitous and ultimately irrelevant, experimental observation can be clearly identified as the turning-point between failure and success. A computing-machine store can be thoroughly tested only by using it in a computing machine, so a small computing machine was built. It worked, and close collaboration with local industry began.

A commercially built computer was installed in the University to gain operational experience to guide future research in machine design. Its appetite was insatiable, so it was made available to outside users. Meantime, improved machines were being designed in the Electrical Department proper, and the engineering and operational aspects of computing machines continue to develop side by side.

The effect of all this on the light-current side of the departmental activity has been, and still is, extremely stimulating; close links with industry have been formed, and a contribution to progress has been made.

The glamour of radar, and later of computing machines, was at one time tending to unbalance the Department in the direction of light-current work. Fortunately, one of my colleagues with a knowledge of textile machinery decided to examine the possibility of electrical shuttle propulsion. For this purpose he built a long linear induction motor designed to move conducting material along a straight line instead of round and round. This novel device excited considerable interest in the Department, and gave rise to many questions which could not be immediately answered. In particular, it posed the question, What would happen if the conducting material were constrained so that it could move only in a direction other than the direction of motion of the magnetic field? From this bit of idle curiosity there has grown up a considerable research effort concerned with the development of brushless variable-speed induction motors, which has already met with some success and has brought another close and valuable contact with industry. It has also revitalized the teaching of heavy electrical engineering and has corrected the balance of interest in the Department.

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SOUTHERN CENTRE: CHAIRMAN'S ADDRESS

By G. BISHOP, B.Sc., Member.

'THE FUNCTION OF THE DEVELOPMENT ENGINEER'

(ABSTRACT *of Address delivered at* PORTSMOUTH 1*st October*, 1958.)

Among young engineers to-day there are many who have little idea of how to set about the development of an entirely new project. Having had considerable experience of this type of work, I thought it would be a good idea to describe how it can be carried out. Fig. 1 shows how the various stages of development which I am about to describe are linked together.

The development engineer is not usually in a managerial position. If he has a good idea for doing some special job or discerns that a certain project needs developing, he goes to the manager and persuades him that such a job needs doing, and that he is the person to do it. I personally find this persuasion the most difficult part of the development. Alternatively the manager may have had orders for a certain equipment, in which case the development engineer is simply told to develop it.

Having been given the job, the development engineer has first to learn what he can about it and the circumstances connected with it. He should then look at the project with an unbiased mind from the broad overall aspect of how it will be used, and of how it will fit into the human chain of development from the manager or director through the research and development stages to the production and distribution stages and finally to the consumers or users.

He must also give consideration to rough schemes of how the complete process should be carried out, and of how the various parts of the equipment will be connected together from the receipt of data or its input, right through to the application of its output.

The choice of scheme will be governed to a large extent by the necessary geographical location of various parts of the equipment, and by whether certain parts need to be manned by operators or not.

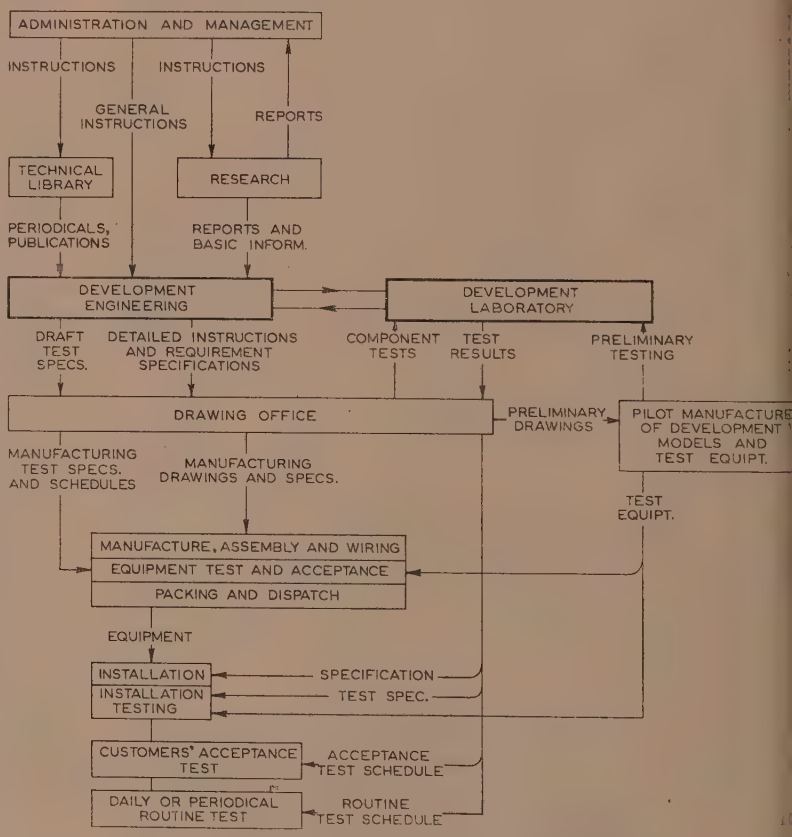


Fig. 1.—General chain of development.

Having decided on a scheme and drawn a rough flow diagram for it, he should consider the general form which the various parts of the flow diagram will take, and also how each part will control or affect the others.

He will then have to consider each part in more detail and

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termine the details of the input and output functions required it, and then the general method of achieving them. It is this rt of the development which should be considered impartially the light of up-to-date knowledge. The chief aim here must to carry out the processes by the simplest and most reliable ethods for which manufacturing resources are available.

Requirement Specifications.—At this stage the development gineer should write a requirement specification for each unit the equipment. When complete the requirement specifica-ons will be passed to individual designers. The detailed design carried out as a joint effort between the designer and the aughtsman in the drawing office, where the manufacturing awings are prepared. This is probably the most arduous and nportant part of the work.

Drawings and Specifications.—Manufacturing drawings and ecifications are the main means by which information is ssed from the design or development stage to the manu-cturing stage. It is important to remember that equipment ust be so designed that it can easily be split up into sub-semblies, and the drawings must be arranged accordingly. his is necessary in order that the assembly of sub-units can take ace in parallel in different sections of the factory, and thus duce the overall production time. It also allows spare sub-semblies to be produced for those items which require frequent rvicing.

Provisional Test Specifications.—While the design is proceed-g, the development engineer will have to consider the tests to hich each individual part and also the whole scheme will be bjected, and will have to write provisional test specifications, which the initial acceptable limits of performance of each rt of the equipment will be laid down.

If a particular part of equipment under test gives trouble due faulty design, it is likely that the design is not correct in rinciple. If this is so, it is best to think from first principles nd completely redesign the part. Merely to modify a part hose design is based on incorrect principles in order to make just work will never give a really satisfactory solution. It is tter to accept the delay and admit one's errors in the early ages than to try to patch them up and run into greater trouble ter, when production quantities may be involved.

Tests and trials are usually carried out on a small number of velopment models in the early stages in order to discover such eaknesses in design. The point must be reached, however, hen further improvements cannot be incorporated if production to proceed. It then becomes necessary to leave any further nprovements for a later design.

Test Equipment.—The design of the production, installation nd routine test equipment is usually a major and difficult part the development. Moreover, this equipment is costly, ecause its standard of workmanship and output must generally of a higher order than those of the equipment which it is quired to test. Unless he gives careful thought to the design test equipment the development engineer is laying up trouble r himself.

Type Approval Tests.—With equipment which is produced in uantity for use under arduous conditions, a sample equipment usually subjected to type approval tests, as described in Inter-rvices Specification K.114, which simulate the worst conditions e equipment will have to withstand during transit, during owage and under working conditions. The application of ese type approval tests is now the rule with new equipment veloped for the Services, and there is no doubt that such tests ould be applied to all equipment which is exported in any uantity, because they quickly show up weaknesses in design.

Test Schedules.—It is usual to prepare a test schedule for each it of equipment. The test schedules consist of standard printed tables, in which the results of the production acceptance tests for each unit are certified by the customer's inspectors. The acceptance limits, and probably a brief description of the method of carrying out the test, are printed at the head of each table, and the test results are inserted in blank spaces.

Packaging.—It is necessary for the designer to specify how each piece of equipment is to be packed for transport or storage and labelled. To help Service engineers in this respect there is a Ministry of Defence publication known as Defence Specification DEF. 1234: 'General Requirements for Packaging Supplies for the Services', which specifies fully many types of packing and containers, and methods of preservation and identification.

Installation Specification.—In order that the various parts of equipment can be installed and set up to work together as a whole, it is necessary for the development engineer to issue instructions for doing so in the form of an installation specification. This will contain or refer to numerous drawings and diagrams. The drawings will consist of such things as site plan layouts, interconnection cabling diagrams, simplified schematics, circuit diagrams, etc. These drawings will also show the methods of mounting equipment, and the method of mechanically lining it up, cable runs, etc.

Installation Test Specification.—This will detail the tests to be applied to the installation, in the correct sequence, to ensure that it will work correctly. In addition, the method of lining up the equipment electrically, and the method of tuning it so that it will give its best or required performance, will be described.

Acceptance Test Schedule.—Before the customer or user accepts an installation he generally carries out acceptance tests, or has them carried out for him by an independent body. These tests are to some extent a duplication of the principal performance tests carried out by the installation test and tuning party, together with an extensive check on all safety devices and a check that all items have been provided satisfactorily by the contractor. These results are written into or recorded in an acceptance test schedule.

Overall Routine Check Test Schedule.—After acceptance, in order to check daily, or periodically as necessary, that an installation is still giving satisfactory performance, a quick overall routine check test is applied. This takes the form of applying settings or test signals at the input of an installation, and recording the response or dial readings at various stages throughout the equipment and at the output. If the outputs and dial readings are within the acceptance limits the installation should be performing satisfactorily. The results are usually recorded on a form known as the overall routine check test schedule.

Operational Handbook.—This handbook should describe the functions of the installation and should state in detail how it is to be operated. Although the development engineer may not actually write the handbook, he will provide the data for it and will have to check it.

Servicing Manual or Maintenance Handbook.—This handbook will describe in full detail, with the use of diagrams, etc., how the installation is to be electrically and mechanically maintained by the maintenance staff. Again the development engineer will have to be certain that its contents are satisfactory.

Schedule of Equipment.—Another booklet which forms an essential part of the installation is the schedule of equipment. This contains the complete list of equipment comprising the installation, a list of ready-use spares kept on site, and a list of base spares kept at bases or depots.

General Service Acceptance Trials.—Where a certain type of equipment is required in quantities, it is usual, after the first prototype has been subjected to all the tests previously mentioned, to hand it over to the user or customer for him to submit it to

tests and trials under actual working conditions, by the personnel who will normally operate and maintain it. This means that it will be subjected to the rigours of actual service by the user without any development staff being in attendance.

Such are the means by which the development engineer passes on his instructions to the next stages in the life of an equipment after development, namely to the stages of production, inspection, distribution, installation or erection, instruction in use and servicing.

Post-Design or Follow-Up Service.—When a development engineer has passed his equipment on to the next stages he is not allowed to forget about it, because manufacture and use of the equipment may bring to light certain difficulties in the manufacture of perhaps a few particular items, or of weaknesses or short useful life in one or two components, which will require changes in design.

In order to relieve the development engineer from such investigation, and to set him free to devote all his energy to any new work he has undertaken in the meantime, it is probably best to have a separate organization to deal especially with this follow-up work.

This summarizes the number of stages through which a new type of equipment has to pass, subsequent to the design stage, and will help to explain why the development of a complex equipment takes such a long time before it comes into general use.

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SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By F. A. BENSON, D.Eng., Ph.D., Associate Member.

'THE ORIGIN AND GROWTH OF ELECTRONICS'

(ABSTRACT *of Address delivered at* SHEFFIELD 15*th October*, 1958.)

The word 'electronics' has only recently appeared in dictionaries but is firmly established in use, and its very usefulness is already rendering it difficult to limit it satisfactorily in scope and application.

The year 1947 marked the jubilee of the discovery of the electron by Sir J. J. Thomson. The emission of electrons by hot bodies (thermionic effect) was investigated by DuFay in 1733, the principle of the valve was observed by Edison in 1883 during his lamp experiments, and the photo-electric effect was studied by several investigators between 1887 and 1889. The work of Plücker and Hittorf between 1850 and 1870 on low-pressure electrical discharges led Crookes to discover cathode rays in 1879, and Röntgen, X-rays in 1885. Then Thomson showed that the thermionic and photo-electric effects were due to the emission of particles identical with those found in the cathode rays of discharge tubes. By 1904 Fleming had made the first practical diode, and two years later the addition of a grid by de Forest produced the prototype of the contemporary radio valve and allowed radio signals to be not only rectified but also generated and amplified. Twenty years after Thomson's discovery, electronic devices were being used extensively in the First World War, and soon afterwards formed the keystone of the world's broadcasting network.

In 1927 it was discovered that the electron could behave as a wave motion as well as a corpuscle. This discovery created much difficulty in the fundamental interpretation of physics, but provided the powerful new tool of electron diffraction for studying the structure of matter, and the electron microscope rapidly found important uses in industry and medicine. During the first four decades after Thomson's discovery, however, the world saw the results of electronics mainly in the application of thermionic valves, photocells and cathode-ray tubes to communication, radio and television, and industry began to use electronic techniques for control purposes.

The Second World War caused a revolutionary change in the science and practice of electronics and gave rise to major new electronics industries. It was perhaps the primary influence which changed electronics from a science auxiliary to physics and electrical engineering to a subject with an independent organization. A great deal of the country's scientific manpower went into either Government research establishments or the electronics industries. This concentration of effort produced important electronic devices as well as affecting the progress of the war. The well-known story of the battle against submarines is a good example of the great influence of an electronic device. After the war many people returned to civilian life carrying some knowledge of the subject with them, and this had an enormous effect in facilitating the spread of electronic apparatus in daily life.

There are few scientific investigations which do not benefit from an application of electronic techniques, but British industry was originally slow in absorbing such benefits. Since the war there has been rapid development of television and the application of radar to provide blind navigation for civil aircraft and ships. Electronics has played an increasingly important role in medicine. Electronic controls are improving the efficiency of industry and freeing more and more people from monotonous routine work.

Electronic technique has recently grown so rapidly that it is difficult to keep up with its expansion. Consider, for example, transistors and computers. It is just over ten years since the transistor was invented. Now diffused-base transistors are orbiting round the earth in satellites, and there is scarcely a country in the world not making some effort on semiconductor development. There is probably not a facet of electronic circuits which has not been affected by transistors. A wide variety of applications required a staggering range of characteristics. Transistor manufacturers had to develop many designs using point, grown, alloy and surface-barrier techniques on germanium and silicon. Each technique had serious limitations, but the possibility of removing most of these came with the diffused-silicon transistor. These devices have cut-off frequencies of 50–100 Mc/s, are 5 to 10 times faster than the older germanium transistors, and have the advantages of high power and high efficiency, and the ability to operate at high temperature. Similar techniques applied to germanium have raised the

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equency into the 1 Gc/s region. Novel semiconductor designs nder development will extend the range of performance; e.g. -region *p–n–p–n* silicon switching diodes for use particularly in l-electronic telephone systems. Diffused-germanium transistors ill probably soon be made for frequencies up to 10 Gc/s. New aterials for transistor applications are being sought among the ompound semiconductors. Hall-effect, thermo-electric and hoto-electric semiconductor devices are becoming more impor-nt in the technology of solid-state electronics. Printed circuits, stead of conventional wiring, have, in conjunction with tran-stors and miniaturized components, helped to simplify much ectronic equipment.

Electronics is now usurping the human functions of detection nd control. Electronic instruments can 'see', 'feel' and 'hear', nd can react to what they find. Electronic machines can take ver some of the contemplative and calculative functions of the uman brain. These computers can read, write, play chess or anslate Russian into English. Modern computers are a result f the application of electronic mechanisms to machines that ere previously restricted in their scope by limitations of echanical techniques.

It is not yet known how far computers will influence our daily ves. They can, for example, be used in weather forecasting nd for carrying out complex calculations associated with tidal ovements. They are also an essential feature of national efence. They react very quickly and can carry out processes hich were impossible with human control, e.g. the manufacture f some chemical products which exist for only a fraction of a second before changing to some other material. Human beings, despite their shortcomings, are very versatile and cannot always easily be replaced by machines. Further, the introduction of automatic mechanisms into industry has naturally aroused some fear that they will result in widespread unemployment. But automation is essential if we are to maintain and increase the productivity of our industries, so that the social and economic problems must be solved. The automatic factory will produce redundancy but will also create new types of job; the proportion of skilled to unskilled workers will increase.

The electronics field is gradually getting more complicated. A television set is more complex than a radio receiver, while colour television is still more elaborate. The technology of microwaves needs more understanding of mathematics and physics than is necessary when dealing with frequencies below 1 Mc/s. Thus, as time goes on, electronic engineers will need more knowledge and a higher level of knowledge. Electronics seems to be rapidly taking over electrical engineering education. As Terman once stated, electrical engineering courses will, in the future, emphasize increasingly the basic sciences at the expense of some traditional engineering subjects. Electronic engineers regularly use differential equations, functions of a complex variable, vector analysis, Laplace transforms, matrices, statistics, probability, electromagnetic theory, solid-state physics, quantum mechanics, etc., but seldom find use for much of the material given in conventional engineering courses on strength of materials, hydraulics, surveying, descriptive geometry, statics, heat engines, etc.

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WESTERN SUPPLY GROUP: CHAIRMAN'S ADDRESS

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By A. G. MILNE, Member.

'ART AND THE ENGINEER'

(ABSTRACT *of Address delivered at* BRISTOL 20*th October*, 1958.)

Engineers should assume a greater responsibility for a solution f the problems thrown up largely by their industry and inventive-ess, which have created the highly industrialized civilization of -day. They should make their presence felt more in everyday fairs—in industry, public life, Parliament and in cultural ursuits.

They must therefore be educated men in the widest sense of e word, with a good knowledge of human achievements in ience, art, and everything else, and with ability both to deal ith hard practical realities and to discuss abstract ideas. The ddress is concerned with the place of art in engineering and the terdependence and overlapping of management and administra-on, science, technology and cultural pursuits—the word 'art' eing used, not in its narrow sense, but with its original meaning f being concerned in every aspect of living.

Though now acknowledged as being undesirable, the dicho-my between the sciences and the humanities persists. The aders of the engineering industries are aware of this and have ointed out that the remedy lies in the broadening of education the schools and universities, where science must be elevated to place beside Latin and Greek. Equally, pursuit of scientific nowledge is no longer sufficient in itself. Science must be joined with other disciplines to produce a balanced, informed and cultured outlook. Neglect of science by humanists, and of the arts by engineers, results in cultural inadequacies in both—deficiencies which are felt in industry, commerce, Parliament and Government.

Sir Julian Huxley, writing on the evolutionary destiny of man, asserts that society should be so organized as to provide opportunities for the fulfilment of its individual members, through adventure and meditation, through the arts, travel and shared activity.

It is suggested that the practising engineer should interest himself in adjoining activities, at work, in advanced management and administration, and at leisure, in public service or culture. The case is argued for professional engineers to be trained for advanced management and administration. They are half-way there by reason of their education and training; it only needs enlightened management to bridge the gap. Equally, engineers must earn the right for enhanced responsibility by broadening their studies and interests.

Great thinkers of the past and present believe that man is unique because of his capacity for conceptual thought as distinct from the instinct and limited intelligence displayed by animals. This is revealed in man's capacity for art, and they ascribe the

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problems of living to-day to the segregation of the various activities of art and the notion that art is not the normal type of human activity.

Reference is made to the Fourth Graham Clark Lecture by Sir Ewart Smith,* in which he urges engineers to acquire a unity of knowledge and experience in science, technology, the humanities and art. He neatly synthesizes the proposition by a graphical illustration of overlapping circles and rectangles representing the four disciplines which serves to show their interdependence.

The last part of the address is devoted to the affinity of the engineer and the artist, and so-called works of art, industrial and everyday objects of utility.

* *Journal I.E.E.*, 1958, **4**, p. 68.

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NORTH-WESTERN MEASUREMENT AND CONTROL GROUP: CHAIRMAN'S ADDRESS

By T. KILBURN, M.A., Ph.D., D.Sc., Member.

'DIGITAL COMPUTING MACHINES'

(ABSTRACT *of Address delivered at* MANCHESTER 28*th October*, 1958.)

The development of large digital computing machines has reached an exciting period in which the potentialities of the second generation of machines are being exploited, while the third generation of machines is being planned and built. It is important to realize that, for many large-scale problems, this new generation of machines will have, in comparison with the first models, an importance at least equal to that which they had in comparison with desk machines. It was often said of first-generation machines that they were a thousand times faster in the solution of problems than a human being with a desk machine. If that figure were true, and it probably is for many problems, the corresponding figure for the new generation of machines will be a million. To emphasize the meaning of these figures the following case may be taken. Since its installation 7½ years ago, the first-generation machine at Manchester University has completed over 30 000 hours of useful computing time. On a third-generation machine an equivalent amount of computation will be done in one day. It is easy to appreciate the profound effect which this increase in speed will have on large-scale problems in the fields of atomic energy and thinking machines, to name but two examples. Leaving on one side the important fact that a problem requiring, say, 3 000 hours on a first-generation machine would not have been done at all because of its length, we are left with the economic facts that it would have cost £75 000 in machine time to solve it, as compared with £750 on a third-generation machine.

If we turn now to the present exploitation of second-generation machines, we see a very interesting picture. At one extreme there is the intensive application to immediate engineering problems, while at the other extreme there is their application to problems which, for the time being, are academic. Examples of the former are the design of transformers, transfer protection, squirrel-cage induction motors, synchronous motors, salient-pole alternators, linear particle accelerators, nuclear reactors, nitric acid towers, crystallography, telephone networks, and so on. Examples of the more academic problems are pattern recognition, and learning and thinking machines.

An interesting combination of these is the programming of the machine in such a way that it learns to recognize patterns. The pattern to be recognized, say **T**, is written on a sheet of paper and is seen by a flying-spot scanner whose output is connected to the machine. A programme in the computer produces a concise statement of what is seen. In the present case this would be a coded version of the description of a **T**, namely a straight line with two free ends, joined at its centre to a straight line with one free end. Initially the computer then says, 'I have not seen this before'. A human being tells the computer by means of a set of switches that this is a **T**. Thereafter, when shown a **T**, the system knows that it is one. Moreover, the system will recognize **T**'s whatever their orientation, over a wide range of size, thickness of line and difference in form, and will ignore any 'noise' caused by breaks in the pattern or dirt on the paper.

A direct attack on the problem of thinking machines has been made by causing a machine to write its own sensible programmes, in response to a question such as, What is the next term in the following series? Since programmes normally are believed to contain the thoughts of the programmer on the problem under solution, programmes written by a machine presumably involve thinking. To date, the most ambitious programme written by the machine has been 23 instructions in length.

In conclusion, it is apparent that the economic and academic exploitation of computing machines is only in its infancy, and that continued efforts should be made in this branch of engineering.

Dr. Kilburn is in the Computing Machine Laboratory, University of Manchester.

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POWER MEASUREMENT AT 4 Gc/s BY THE APPLICATION OF THE HALL EFFECT IN A SEMICONDUCTOR

By L. M. STEPHENSON, B.Sc.(Eng.), Graduate, and Professor H. E. M. BARLOW, Ph.D., B.Sc.(Eng.), Member.

(*The paper was first received 2nd July, and in revised form 6th August*, 1958.)

SUMMARY

When a semiconducting crystal is mounted in the path of an electromagnetic wave, a Hall e.m.f. is set up in the material along the direction of propagation with a value proportional to the power transmitted. The device operates most satisfactorily when the wave impedance is small, so that for a given power the electric-field component is reduced to a minimum. The use of a resonant cavity with the crystal erected in it at a point of strong magnetic field enables such favourable conditions to be established, and this arrangement forms the basis of the wattmeter described. The instrument is capable of measuring power at 4 Gc/s with an error of ±3% from 30 mW to about 20 watts, and with the unique feature that this performance can be achieved at any standing-wave ratio between unity and 0·1 while absorbing only about 3·4% of the power measured.

Some experiments on semiconductors mounted directly in a waveguide are also described, showing the possibility in this case of using several crystals in cascade.

(1) INTRODUCTION

In an earlier paper[1] the authors described a wattmeter employing the Hall effect produced in a germanium crystal when mounted in a resonant cavity magnetically coupled to the waveguide carrying the power. This instrument has now been much improved, and in its new form it is capable of measuring powers from 3 mW to about 20 watts at 4 Gc/s with an error of ±3%. Moreover, this performance can be achieved at any standing-wave ratio between 1·0 and 0·1 while absorbing only about 4% of the power measured. The calibration may conveniently be carried out so that the power actually absorbed by the load is recorded directly. Details of this wattmeter and the technique used in its application are described here, together with some experiments directed towards establishing an alternative type of instrument capable of operation over a wider band of frequencies.

(2) THE RESONANT-CAVITY WATTMETER

(2.1) Construction of the Instrument

The arrangement shown in Fig. 1 is similar in principle to that described previously, but it incorporates a number of refinements. A rectangular H_{01} resonant cavity about one wavelength long is magnetically coupled by means of a narrow slot to the main waveguide carrying the power to be measured, and the semiconductor crystal is mounted at the centre of this cavity, where the magnetic field is a maximum and the electric field is zero. A small current is then fed into the crystal by means of a probe connected to it and projecting slightly into the main guide through the centre of the coupling slot. This probe picks up a displacement current which, for comparatively low-impedance crystal circuits, is approximately in time quadrature with the electric field in the main waveguide, while the magnetic field in the cavity at resonance is likewise almost in time quadrature with the magnetic field in that guide. Two tuning screws are provided, one projecting through each end of the cavity, and a geared shaft between them enables them to be driven into or out of the cavity simultaneously, thus maintaining the electrical symmetry of the arrangement about the centre point at which the crystal is mounted. Independent movement of the tuning screws is also possible, so that preliminary adjustments can be made to establish the required symmetry. The magnitude and phase of the current through the crystal relative to the magnetic field applied to it by the excitation of the cavity can be adjusted over quite a wide range by using crystals of different resistivity and different dimensions or by using current leads to the crystal of different diameters. According to the particular phase adjustment employed, two alternative techniques can be applied in making power measurements.

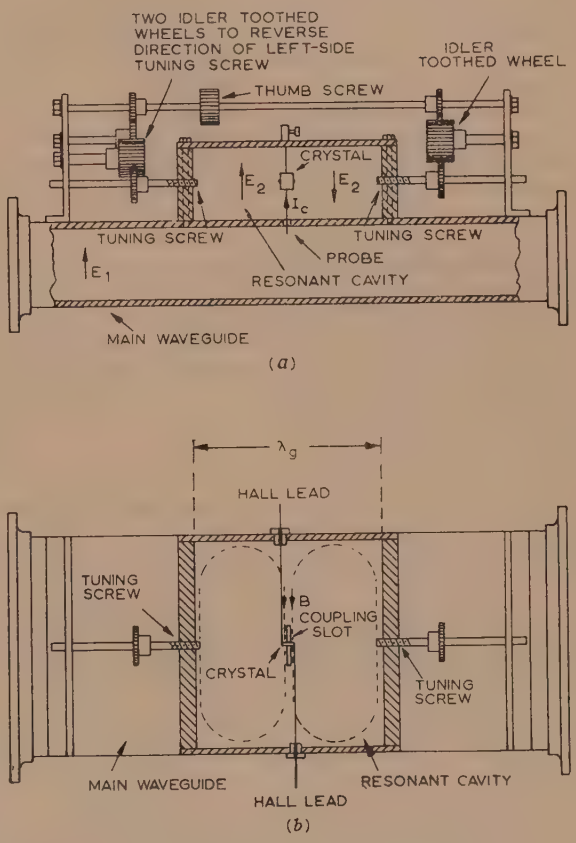


Fig. 1.—Resonant-cavity wattmeter.
(*a*) Elevation.
(*b*) Plan.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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(2.2) Technique of Operation for 'In Phase' Adjustment

When setting up the instrument the first step is always to establish electrical symmetry of the resonant cavity with respect to the crystal. This can be readily achieved by exciting the cavity from a pure standing wave in the main waveguide, so located that a maximum of magnetic field occurs opposite the coupling slot and therefore no current is picked up by the probe. In these circumstances, the Hall leads attached to the crystal should give zero output and the tuning screws must be independently adjusted while maintaining the cavity at resonance to ensure that this is so. The next consideration is to provide for the proper phasing of the crystal current picked up from the main guide in relation to the magnetic field of the cavity. With a matched load these quantities should, in the present case, be in time phase. This is achieved primarily by suitable choice of crystal and its leads. The particular crystal unit used was of 37 ohm-cm n-type germanium, 0·2 cm × 0·2 cm × 0·075 cm, with 32 s.w.g. tinned-copper wires soldered to it for the current and Hall leads. Experience in soldering to such crystals enabled rectifier action at the contacts to be substantially eliminated for the very small currents employed. The final phase adjustment can conveniently be made without introducing any serious error by simultaneous movement of the two tuning screws, giving a condition for which the cavity may be just off resonance. The required setting having been established, the instrument may be applied without further preparation to measure power at any standing-wave ratio simply by using the appropriate calibration figure of proportionality between power and Hall e.m.f. To obtain the power factor of the load accurately, the following supplementary measurements were found to be helpful. The cavity was detuned by joint movement of the two tuning screws to the half-power points on each side of the 'in-phase' adjustment (so that the amplitude of the magnetic field, B, fell to $B/\sqrt{2}$) and then the algebraic difference between the corresponding Hall output readings was taken, giving, as shown in Fig. 2(a), a measure of the reactive power.

(2.3) Technique of Operation for 'Quadrature' Adjustment

In the neighbourhood of resonance the phase of the magnetic field in the cavity changes rapidly with frequency, and an alternative procedure—which was shown to yield greater accuracy for power measurements when the stability of the microwave source could not be guaranteed—was as follows. The phasing of the current through the crystal was adjusted so that with the cavity tuned to resonance the Hall output corresponded to the reactive power (i.e. no output on matched load). This was made possible by using a crystal circuit whose resistance was high and whose inductive reactance annulled the inherent capacitive reactance of the associated probe element. The crystal employed in this case was of 37 ohm-cm n-type germanium with dimensions of 0·22 cm × 0·19 cm × 0·03 cm and having 44 s.w.g. current leads soldered to it. Measurements with this arrangement were made by detuning the cavity to the half-power points on each side of the resonant setting. The algebraic difference between the Hall outputs at these half-power points is then the 'true' power [see Fig. 2(b)]. This technique gave the most consistent observations and the calibration results reported here were obtained by its use. Rectifier action proved to be quite negligible, and a linear relationship between power and Hall e.m.f. was obtained whatever the nature of the load.

(2.4) Calibration of the Instrument

Fig. 3 shows the calibration curve, employing as the standard of comparison a differential air thermometer of the type developed by Gordon-Smith.[2] The power absorbed by various

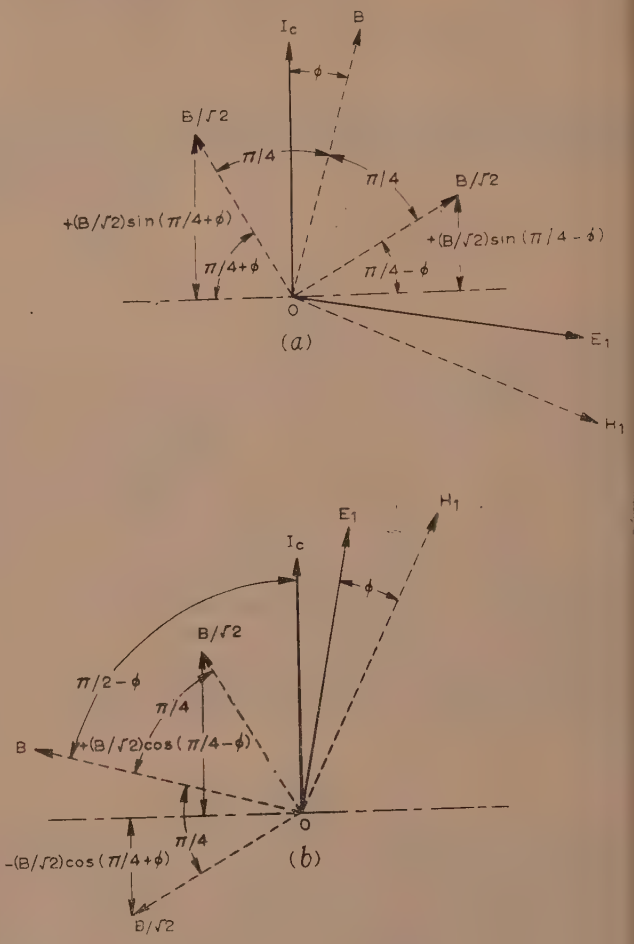


Fig. 2.—Vector diagrams.

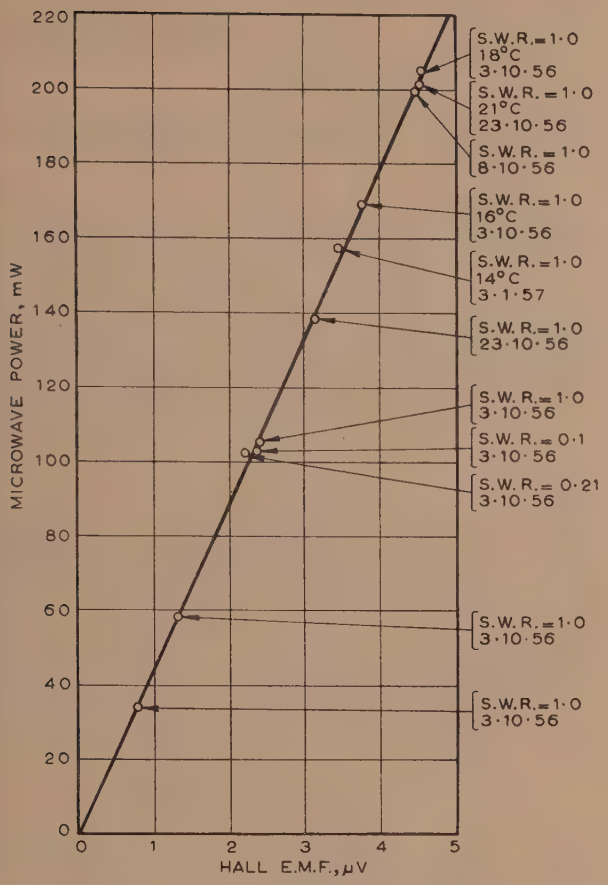
E_1 = Electric field in main waveguide.
H_1 = Magnetic field in main waveguide.
B = Magnetic flux density in cavity.
I_c = Current through crystal.

(a) Reactive power measurement with instrument set to read 'true' power at resonance. Hall e.m.f.'s are $V_c' = \frac{K}{\sqrt{2}} I_c B \sin\left(\frac{\pi}{4} + \phi\right)$ and $V_c'' = \frac{K}{\sqrt{2}} I_c B \sin\left(\frac{\pi}{4} - \phi\right)$, so that $V_c' - V_c'' = KI_cB \sin\phi$ = reactive power component.

(b) 'True' power measurement with instrument set to read reactive power at resonance. Hall e.m.f.'s are $V_c' = \frac{K}{\sqrt{2}} I_c B \cos\left(\frac{\pi}{4} - \phi\right)$ and $V_c'' = -\frac{K}{\sqrt{2}} I_c B \cos\left(\frac{\pi}{4} + \phi\right)$, so that $V_c' - V_c'' = KI_cB \cos\phi$ = 'true' power.

loads giving standing-wave ratios from 0·1 to 1·0 and at ambient temperatures ranging from 14 to 21° C was measured over a considerable period with a sensitivity which remained constant at 22·3 μV/watt. A combined photocell-galvanometer-amplifier unit was used to record the Hall e.m.f., and although the calibration of the wattmeter with the air thermometer was restricted to an upper power limit of 200 mW, a check was made on the instrument with a tapered water load at 5·2 watts, and it was estimated that powers up to 20 watts could be recorded without overheating the crystal. The instrument reading ordinarily includes the power absorbed by the cavity (amounting in this case to 3·4% of the power in the main waveguide) as well as the power dissipated by the load. In some applications it was convenient to offset the reading of the instrument so that the load power alone was given without the need to allow for the loss in the instrument itself.

No precise measurement was made of the Q-factor of the cavity containing the crystal, but this was known to be about 4000, so that tuning was not very critical and was unaffected



g. 3.—Calibration curve for resonant-cavity wattmeter at 4·22 Gc/s.
Sensitivity = 22·3 μV/watt ± 3% for s.w.r. = 1·0 → 0·1.

minor changes in frequency.* At the same time, there are plications for which a wider-band instrument would be sirable, and some preliminary work was done towards this jective.

SOME EXPERIMENTS ON A BROAD-BAND TRANSMISSION-TYPE WATTMETER

(3.1) Arrangement of Apparatus

In approaching the design of a wattmeter capable of use thout readjustment over a wide band of frequencies it was cided to employ a crystal mounted directly in the waveguide rrying the power to be measured (Fig. 4). Some experiments ade previously at 10 Gc/s with this arrangement[3] used short axial lines terminated by pistons for tuning purposes on the d of the current lead to the crystal and on each of the two all leads, thus making the instrument very frequency sensitive. e present plan was to avoid, if possible, any tuning devices, ying upon the choice of a long thin crystal of relatively low istivity capable of being rotated in the *H*-plane about the s in which the Hall leads lie, to establish the required electrical nmetry. No wires were attached to the crystal for the purpose supplying current to it, and consequently there was no means adjusting the phase of that current except by the choice of stal used. One of the problems in this type of instrument is t the crystal, being mounted directly in the waveguide, is rmally required to operate with an applied magnetic field of

The frequency range given by the tuning screws used in this prototype instrument about 30 Mc/s. The central operating frequency could also be varied by movet of the end walls of the cavity, although this required resetting the tuning screws escribed in Section 2.2.

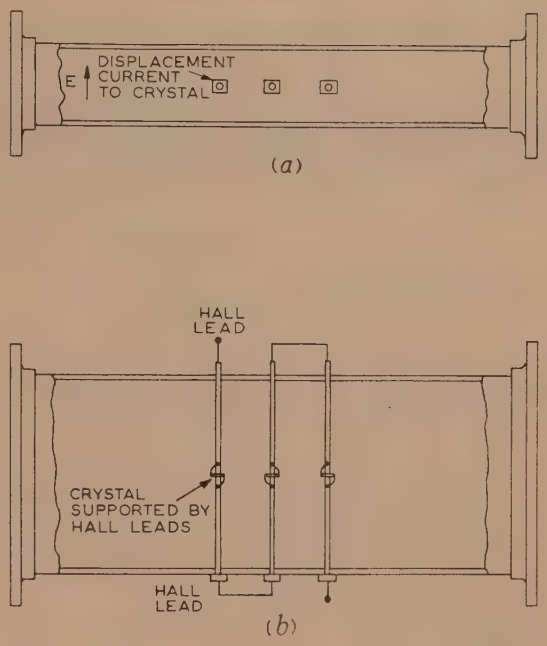


Fig. 4.—Transmission-type wattmeter with three crystals.
(*a*) *E*-plane section of waveguide.
(*b*) *H*-plane section of waveguide.

only about one five-hundredth of the corresponding electric field. Thus, to obtain the necessary sensitivity, the current through the crystal must be several times larger than would otherwise be considered desirable. The use of current of this magnitude, not only increases the unbalanced rectifier output at the Hall contacts, but also tends to introduce a thermal gradient between these contacts under standing-wave conditions. Reference to this thermo-electric effect was made previously,[3] and it was pointed out that, when a stationary wave pattern exists in the waveguide with a crystal only a millimetre or two long along the direction of propagation, significant temperature differences can arise between the two Hall contacts, yielding an unbalanced thermal e.m.f. To overcome the difficulty the power transmitted along the waveguide was modulated at 3 kc/s, to which thermal effects could not respond, and the output from the Hall leads was recorded after being passed through a narrow-band amplifier tuned to that frequency. The crystal employed in these experiments was of 11 ohm-cm *n*-type germanium, having dimensions of 1 cm × 0·165 cm × 0·012 7 cm, and Hall leads of 44 s.w.g. tinned-copper wire were soldered to it after the surface had been etched. The width of each contact was less than the diameter of the wire, and great care was taken to minimize residual rectifier action, but at the level of currents used this was by no means negligible. The crystal was supported by the Hall leads and could be rotated with these leads about their axis.

(3.2) Results Obtained with Transmission-Type Apparatus

Despite all the precautions taken, the residual rectifier output was found on occasion to be as much as five times the Hall output. In these circumstances it is clearly not justifiable to separate the Hall component by taking the difference between the outputs from the crystal with power flowing first in one direction and then in the other. The reflection coefficient presented by the crystal was not necessarily the same in the two directions. Moreover, since a finite power (1% of the power in the waveguide) was absorbed by the crystal, the side on which the wave was incident tended to be at a slightly higher tem-

perature than the remote side, possibly causing some change in the residual rectifier output. By rotating the crystal with its associated Hall leads about the *H*-axis of the waveguide, an angular position was found for which the rectifier output was a minimum, and under these conditions a linear relationship was found between power in the guide and Hall output as determined by the technique of reversing the crystal unit in relation to the direction of power. The calibration curve shown in Fig. 5 was obtained in this way, the Hall output being easily distinguishable from the residual rectifier output, which remained non-linear.

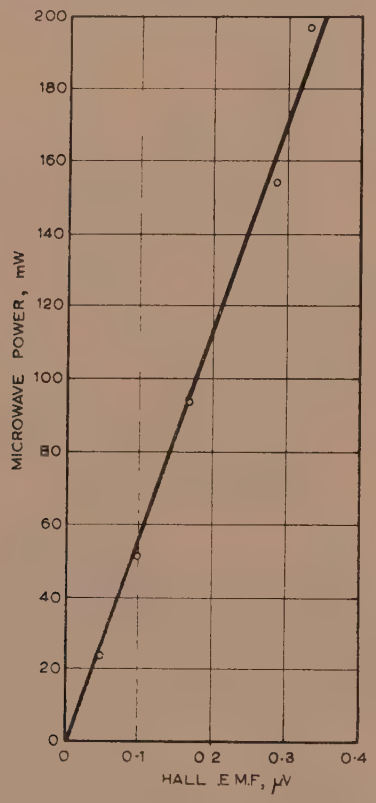


Fig. 5.—Calibration curve for transmission-type wattmeter at 4·22 Gc/s.
Sensitivity = 1·8 μV/watt ± 6% with single crystal.

The Hall coefficient deduced from estimated values of the electric and magnetic field strengths in the vicinity of the germanium crystal when giving known Hall outputs was 9×10^{-2} m^3/coulomb, which compares with the theoretical d. value of $4{\cdot}6 \times 10^{-2}$ m^3/coulomb.

(3.3) Conclusions from Experiments and Suggestions for Further Work

Although the precise arrangement employed here, embodying a single germanium crystal mounted in the main waveguide cannot be regarded as the basis of a practical wide-band instrument, it seems likely that the further development of semiconductors like indium arsenide in the form of thin films together with improved techniques for eliminating rectifier action, will make possible a really satisfactory wattmeter of this general type. If such an instrument (having a single crystal) is to measure true power, independent of standing-wave ratio, the crystal current must be in phase with the electric field in the waveguide. Without tuning elements—which tend to be frequency sensitive—this would be difficult to achieve, but when two crystals are mounted in the waveguide $\lambda_g/4$ apart, with their outputs connected in series, the Hall voltages arising from the 'true' power add together, while those arising from the reactive power practically cancel one another. Improved performance can be obtained by several such crystals separated from one another by a quarter of the guide wavelength and connected with their outputs in cascade. This arrangement will give, not only greater sensitivity, but also a more accurate measure of the 'true' power, whatever the nature of the load.

(4) ACKNOWLEDGMENTS

The authors are grateful to the Trustees of the R. W. Paul Instrument Fund for financial support of this work, and they also wish to acknowledge the valuable help given by Mr. H. G. Effemey in developing the experimental techniques.

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MEASUREMENTS OF NON-LINEARITY IN CRACKED-CARBON RESISTORS

By G. H. MILLARD, B.Sc., A.Inst.P.

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SUMMARY

The non-linearity of a number of small cracked-carbon resistors has en investigated at both audio and radio frequencies. In the case of e resistor, non-linearity coefficients of order higher than the third re measured; their effect is considered for various levels of the ut signals. The degree of non-linearity encountered would be gligible for most purposes.

(1) INTRODUCTION

It is well known that carbon resistors are inherently non-linear, en when the temperature is held constant, and their perfor- ance in this respect is usually described in terms of the 'voltage efficient', which is defined as follows. The maximum rated ltage V_1, having regard to the power rating and voltage limita- ns specified, is applied to the resistor and its resistance, R_1, measured. The time the resistor passes current must be kept fficiently short during this measurement for it to suffer gligible change of temperature. A second measurement is ade with an applied voltage V_2 equal to one-tenth of the aximum rated voltage, giving a resistance R_2. The 'voltage efficient' of the resistor is then given by

$$\frac{100(R_1 - R_2)}{R_2|(V_1 - V_2)|}\%$$

The effect is appreciable for resistors of high value, say greater an 10 kilohms, and can be measured on a d.c. resistance bridge. r lower values the method is inaccurate, since the change in nperature of the resistor due to heating results in a change of sistance comparable to that which it is desired to measure. e paper describes alternative methods based on measurements the amplitudes of harmonics and intermodulation products. e measurements were limited to resistors of low value (50–0 ohms), in which the observed non-linearity was very small. would be negligible in most applications.

Interest in the problem arose in connection with measurements out-of-band signals at v.h.f. transmitting stations. It was quired to measure very weak intermodulation products in the esence of two strong v.h.f. signals, but a part of the measuring stem, a reflectometer embodying cracked-carbon resistors, peared to be contributing to the intermodulation.

The intermodulation products in question have frequencies $f_2 - f_1$), $(2f_1 - f_2)$, where f_1 and f_2 are the intermodulating quencies and arise from odd powers in the voltage/current v.[1] Accordingly no attempt was made to measure harmonics intermodulation products arising from even powers. In any se, preliminary measurements had shown that such products re small compared with the odd-order products.

The majority of the measurements were made at audio fre- encies. In order to avoid any doubt regarding the validity applying the results to very-high radio frequencies, some nfirmatory measurements were made at 90 Mc/s.

(2) AUDIO-FREQUENCY MEASUREMENTS

(2.1) Experimental Arrangement

A pure signal was applied to the resistor in a bridge circuit. The harmonic frequencies appearing across the balance terminals of the bridge were amplified and measured. This method has been used by Rosenthal and Louis[2] and by Mulders[3] for measuring the voltage coefficients of resistors in the range 1–20 kilohms, where non-linear effects are appreciably greater.

A block schematic of the experimental arrangement is shown in Fig. 1. The resistor under test, R_x, formed one arm of a

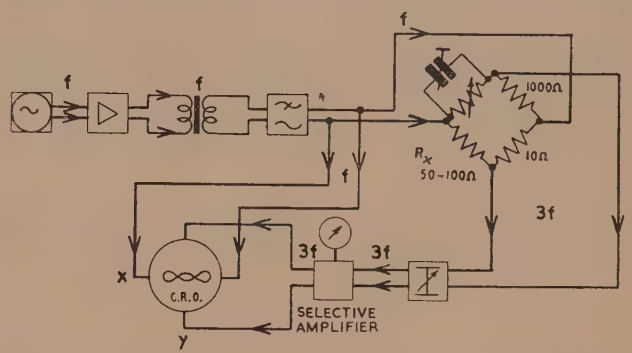


Fig. 1.—Experimental arrangement for audio-frequency measurements.

bridge circuit whose balance was largely independent of frequency; this helped to reject harmonics from the source. Harmonic frequencies generated in the resistor from an applied signal of 1·06 kc/s were amplified by a high-gain selective amplifier and detected for a meter display. The amplitude of the harmonic relative to the signal at fundamental frequency was measured by establishing across the resistor a known voltage at the harmonic frequency, with the source at the fundamental frequency disconnected, and adjusting the attenuator to give the same meter reading as before; this procedure took into account the attenuation between the resistor and the balance terminals.

The output of the selective amplifier was also connected to the Y-plates of an oscilloscope. The input for the X-plates was derived from the voltage at fundamental frequency applied to the bridge. The display on the oscilloscope, a Lissajous figure, accordingly gave an indication of the phase of the third harmonic relative to that of the fundamental frequency, as modified by the constant phase shift in the amplifier.

The sensitivity of the arrangement was such that, with maximum power (0·5 watt) being dissipated in the resistor, a level of third harmonic about 135 dB lower could be detected. This high sensitivity was achieved by taking particular care over earthing arrangements and the disposition of the apparatus.

(2.2) Thermal Cycles

It was thought possible that the generation of third harmonic in the resistors might be due to the temperature varying cyclically with the applied voltage. The third-harmonic waveform generated from such thermal cycles would be expected to be retarded

Written contributions on papers published without being read at meetings are ted for consideration with a view to publication.
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relative to the fundamental waveform, whereas that from an instantaneously non-linear resistance should be in phase with the fundamental.* The observations of the phase of the third harmonic, though not precise, indicated that thermal cycles were not important.

As an additional check on the effect of thermal cycles, the fundamental frequency was raised to 3·3 kc/s. The sensitivity of the arrangement was then somewhat less, the lowest detectable level being about 120 dB below that of the fundamental frequency.

(2.3) Experimental Results

The performance of resistors of different power rating may be compared by quoting the level of third harmonic below that of the fundamental, for a value of the latter equal to a given fraction of the nominal rating. For reasons given in Section 3.3, a figure of one-tenth of the nominal rating was chosen for this purpose. The level of third harmonic at one-tenth power rating was, in most cases, interpolated from a number of measurements at different levels of the fundamental. In the case of the two largest resistors, all the measurements were made at levels lower than one-tenth power rating, and the results given for these resistors are extrapolations made on the assumption that only third-order non-linearity was significant. This assumption implies that the level of third harmonic will then vary as the cube, and the relative level as the square, of the level of the fundamental frequency.

together. The difference of 12 dB between the measurement a 1·06 kc/s and that at 3·3 kc/s on resistor 4 is thought to be du to instability of the unusually high non-linearity in this resisto Apart from this case, the levels obtained in measurements a 3·3 kc/s are on the average 2 dB lower than those obtained a 1·06 kc/s; this difference is thought to be due to greater ina curacy of measurement arising from the higher noise level a 3·3 kc/s. For the same frequency change, the third harmoni due to the thermal cycles of a lamp filament was observed t decrease by 13 dB, i.e. 3 dB more than the expected change.

The sign of the coefficient of third-order curvature in th voltage/current law, a_3, was deduced by comparing the oscillo scope display with that obtained when two germanium crystal were connected together in opposite senses to the 'unknown terminals of the bridge through an attenuating pad of wire wound resistors; the coefficient was found to be negative in a cases.

In the course of the measurements of out-of-band signals a v.h.f. transmitting stations, which were mentioned in Section fifth-order intermodulation products were detected, indicatin powers higher than the third in the voltage/current law to b significant. Accordingly in one case (resistor 1B of Table 1) search was made for harmonics higher than the third; only th fifth harmonic could be measured. Using this measurement, th level of fifth harmonic expected from a signal at one-tenth o the resistor rating, assuming no order higher than fifth to b significant, would be −180 dB. Taking this as a measure of a_5

Table 1

MEASURED LEVELS OF HARMONICS AND INTERMODULATION PRODUCTS FOR LEVEL OF FUNDAMENTAL EQUAL TO ONE-TENTH OF NOMINAL RATING

Resistor	Resistance	Nominal rating	Measured level of third harmonic relative to fundamental at		Level of $(2f_2 - f_1)$ intermodulation product relative to fundamental		
					Predicted from measurements at		Measured at 90 Mc/s
			1·06 kc/s	3·3 kc/s	1·06 kc/s	3·3 kc/s	
	ohms	watts	dB	dB	dB	dB	dB
1A	70	$\frac{1}{8}$*	−119	−124	−109	−114	
†1B	65	2 × $\frac{1}{8}$*	−118	−120	−108	−110	−110
1C	70	$\frac{1}{8}$*	−106		−96		−100
2	70	$\frac{1}{4}$*	−122	−126	−112	−116	
3A	70	$\frac{1}{8}$*	−134	−136	−124	−126	
3B	52·6	$\frac{1}{8}$*	−128		−118		
3C	90·9	$\frac{1}{8}$*	−128		−118		
3D	70	$\frac{1}{8}$*	−132		−122		−125
4	49·8	$\frac{1}{4}$	−97	−109	−87	−99	
5	70	7·5	−133		−125		
6	70	55	<−125		<−120		<−93
7A	75	$\frac{1}{2}$	−138	−132	−128	−122	
7B	50	$\frac{1}{2}$	−130		−120		−124
8	75	$\frac{1}{4}$	−132		−122		
9	75	$\frac{1}{2}$	−126	−130	−116	−120	
10	75	1	−131		−121		<−126

* The manufacturer has since doubled these ratings for the same resistors.
† Two resistors in parallel.

In Table 1 the measured levels of third harmonic are given in decibels relative to a level of the signal of fundamental frequency equal to one-tenth of the nominal power rating. The resistors are numbered according to type, similar types being grouped

the coefficient of fifth-order curvature in the voltage/current law the level of third harmonic from a_5 should be five times,[1] o 14 dB, higher than the level of fifth harmonic from a_5, namel −166 dB. This is much smaller than the measured total leve of third harmonic (−118 dB), which may therefore be attribute solely to a_3 with negligible error.

* In the paper two quantities alternating at frequencies harmonically related are said to be 'in phase' when they pass through zero in the same direction at the same time.

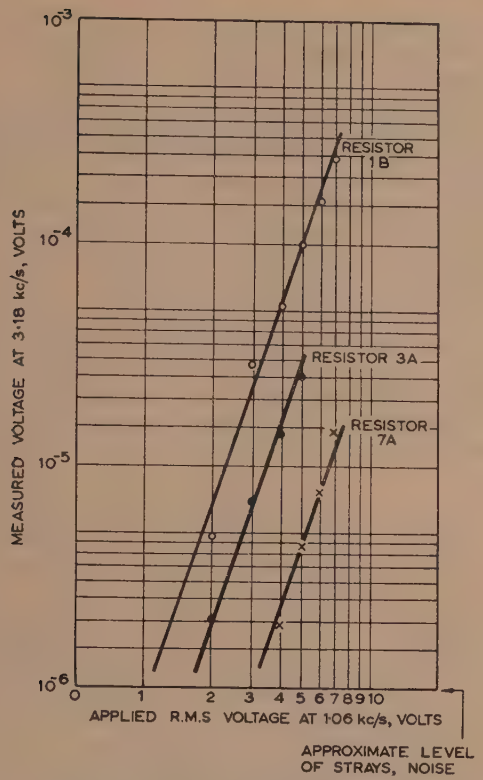


Fig. 2.—Measured variation of third-harmonic amplitude with fundamental amplitude.

Contributions from a_5 may be considered appreciable when)dB below those from a_3. This point is reached in the case of sistor 1B for a signal level of three times the nominal rating, e. 0·75 watt. In other words, the amplitude of the third armonic should vary as the cube of the fundamental amplitude p to a level of the latter of 0·75 watt. The observed variation third-harmonic amplitude with fundamental amplitude is own in Fig. 2 for three resistors. It may be seen that the law cubic within the accuracy of measurement.

The last three columns of Table 1 show the predicted levels of e intermodulation products at frequencies $(2f_2 - f_1)$ and $f_1 - f_2)$ which would be obtained from signals at two funda- ental frequencies, f_1 and f_2, each at a level equal to one-tenth of e resistor rating. These intermodulation products will have ree times the amplitude of the third harmonic, provided that ntributions from higher-order terms may be neglected.[1]

(3) RADIO-FREQUENCY MEASUREMENTS

(3.1) Experimental Arrangement

The outputs of two oscillators operating in Band II (88– Mc/s), with a 4·4 Mc/s frequency separation, were combined rough two sharply-tuned filters (Fig. 3). The combined out- ts passed through a directional coupler into the load under amination. Intermodulation products generated in the load ere observed by a receiver connected to the backward output the directional coupler. In order to prevent intermodulation the receiver, two additional filters, tuned to reject the oscillator equencies, were inserted in the input lead.

The insertion loss of each filter was about 40 dB at the stop equency and less than 1 dB at the pass frequency. The power ssipated in a matched 70-ohm load was about 100 mW at each ndamental frequency.

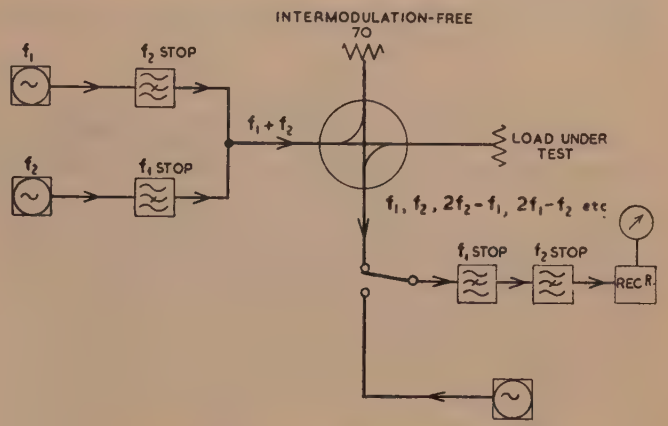


Fig. 3.—Experimental arrangement for radio-frequency measurements.

The oscillator conversion losses for the generation of intermodulation products at the respective anodes were thought to be at least 80 dB, since, with the arrangement of Fig. 3 and the receiver connected to the forward output of the directional coupler, the relative levels of intermodulation products were no greater than −120 dB.

In the course of the measurements, precautionary observations were made of intermodulation in the receiver. This became discernible when the level entering it at each fundamental frequency exceeded 0·5 μW. The receiver was exceptionally well screened and no trouble due to pick-up from the oscillators was encountered. Because of the very high level differences encountered in these measurements, meticulous care was necessary in eliminating intermodulation due to imperfect contacts.

For the sake of simplicity, the amplitudes of the two fundamental frequencies were always kept equal. For the same reason, the majority of measurements were confined to one particular intermodulation product, namely that at the frequency $(2f_2 - f_1)$.

(3.2) Results

The results are shown in the final column of Table 1, where they may be compared with the relative levels calculated from the audio-frequency measurements. The mean difference between measurements at 1·06 kc/s and those at 90 Mc/s is less than 4 dB; this is comparable with the difference between the two audio-frequency measurements and is in the same direction.

For the r.f. measurements the output power of each signal was 112 mW. The figures given in Table 1 for a level at one-tenth rating were deduced from the measurements by assuming a cube-law variation with a fundamental amplitude.

(3.3) Higher-Order Products

The amplitude of an intermodulation product will be the sum of components arising from the terms in the expression

$$v = a_1 i + a_3 i^3 + a_5 i_5 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $i = i_0 (\cos 2\pi f_1 t + \cos 2\pi f_2 t)$.

Accordingly, the amplitude of the component of frequency $(2f_2 - f_1)$ for peak current i_0 will be the sum of an infinite series*

$$v_{(2f_2 - f_1)} = \frac{3}{4} a_3 i_0^3 + \frac{25}{8} a_5 i_0^5 + \frac{735}{64} a_7 i_0^7 \quad . \quad . \quad . \quad (2)$$

* It is assumed that consideration is restricted to the range of values of the peak current i_0 for which these series are convergent.

Similarly, the amplitude of the component of frequency $(3f_2 - 2f_1)$ is given by*

$$v_{(3f_2-2f_1)} = \frac{5}{8}a_5 i_0^5 + \frac{245}{64}a_7 i_0^7 \quad . \quad . \quad . \quad . \quad (3)$$

The amplitude of the component of frequency $(2f_2 - f_1)$ will have a cube-law variation with i_0 only when the latter is small, i.e. when the contributions from higher-order terms are negligible. As i_0 is increased, the departure from cube law gives an indication of the signs of a_5, a_7, etc., relative to a_3. For example, if a_3, a_5, a_7, etc., all have the same sign, the $(2f_2 - f_1)$ product will rise more steeply than cube law. Fig. 4

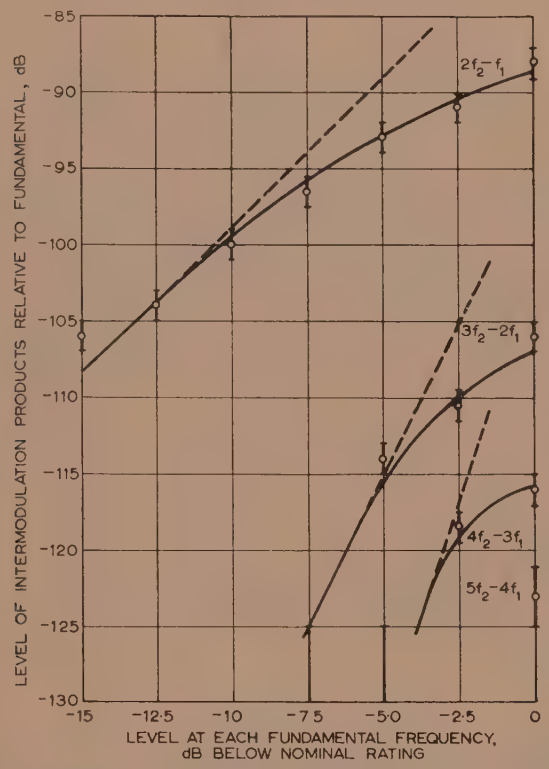


Fig. 4.—Measured variation of levels of intermodulation products. Resistor 1C. Nominal rating $\frac{1}{8}$ watt.

shows the measured variations with fundamental amplitude of all the intermodulation products that it was possible to measure in the case of resistor 1C. It will be seen that the amplitude of each product measured rises initially at the rate expected if higher-order contributions are negligible. Thereafter, the slope becomes less in each case. This can only mean that a_9 is of opposite sign to a_7, that a_7 is of opposite sign to a_5, and that a_5 is of opposite sign to a_3. Using the results shown in Fig. 4 to evaluate the coefficients a_3, a_5 and a_7, the characteristics of resistor 1C may be defined:

$$v = 70{\cdot}8i_0 - 3{\cdot}1i_0^3 + 1{\cdot}2 \times 10^2 i_0^5 - 2{\cdot}4 \times 10^4 i_0^7$$

* See footnote on previous page.

where i_0 is restricted to values below the maximum at whi measurements were made, namely 6×10^{-2} amp.

For resistor 1C, it will be seen that terms of order abo the third are significant when the level of each input signal equal to the nominal power rating, but are negligible at o tenth power rating. Since this resistor shows a large degree non-linearity, it seems reasonable to assume that high-or terms may be neglected for all resistors used, when the level each input signal is one-tenth power rating; this level is theref used as the basis for comparison in Table 1.

Since the two smallest resistors (1C and 3D) were measured a level approaching the nominal power rating, there is an er introduced by assuming third-order non-linearity when ext polating to a level of one-tenth power rating. This er amounted to 7 dB for resistor 1C, for which the corrected le is given in Table 1. For resistor 3D the error could not determined as there was insufficient sensitivity available.

(4) CONCLUSIONS

Measurements made at audio and radio frequencies of thi order non-linearity in a number of small cracked-carbon resist show good agreement, thereby demonstrating the validity applying at radio frequencies the results of measurements audio frequencies. In the case of one resistor, measureme were also made of fifth- and seventh-order non-linearity.

Relative levels of third-order intermodulation products about −110 dB may be expected when a cracked-carbon resis is subjected to the sum of two sinusoidal signals each at a le equal to one-tenth of the nominal power rating, with a variati of about ±20 dB between different types of resistors. Wh the two components of the signal are each at a level equal the nominal rating of the resistor, products of order higher th the third will be significant and the relative level at frequenc $(2f_1 - f_2)$ and $(2f_2 - f_1)$ will be -100 ± 20 dB.

The measurements show that there was significant intermo lation in the transmission-line reflectometers mentioned in S tion 1 and have provided useful data for the design reflectometers in which intermodulation products are negligib

(5) ACKNOWLEDGMENTS

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DESIGN AND PERFORMANCE OF A NEW LOW-NOISE TRIODE FOR USE UP TO 1000 Mc/s

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SUMMARY

he paper outlines the factors governing the design of a simple s-base u.h.f. amplifier valve and considers the circuits in which it be used.

he design of such a valve is described, together with the special niques which are necessary to obtain reproducibility with inter-rode clearances of only 40 microns.

etailed information is given on the stability, noise performance gain-bandwidth product of the valve over the u.h.f. band.

(1) INTRODUCTION

is only fairly recently that much attention has been given to part of the u.h.f. band between 300 and 1 000 Mc/s and it is resting to see why this band was for so long ignored.

onventional valves, with reasonably small clearances, have some time found applications for frequencies up to about Mc/s. They will operate as oscillators at frequencies much ier than this, but in amplifiers, any attempts to obtain a onable gain make the valves unstable.

n the microwave region, the advent of the klystron and mag-on made available sources of power for frequencies above 0 Mc/s and circuit techniques soon reached an advanced e, the associated receivers invariably using crystal mixers as first stage.

he development of the disc-seal valve, somewhat later than klystron, vastly extended the operating frequency-range of space-charge control valve, but nearly all the applications e dictated by the coverage of the klystron and the magnetron. his left a gap in the frequency range in which, for a long time, e was no activity. The recent increased interest in the band, such applications as television, posed the question: Can a s-base valve be made, using techniques applicable to relatively e-scale production, which would operate at frequencies up 000 Mc/s?

he disc-seal valve would give satisfactory performance, but many applications it is deemed too costly and the associated uitry is too involved and bulky. Alternatively, receivers with ystal-mixer first stage have been used to a limited extent, but r.f. amplifier first stage offers a number of advantages and e are outlined later.

n the paper, the reasons for the inability of conventional s-base valves to operate as amplifiers in the u.h.f. range are ussed, together with the advantages to be gained by operating es in the earthed-grid connection.

inally, a practical design for a suitable glass-base valve is sidered, together with various measurements carried out on valve.

(2) CIRCUIT CONSIDERATIONS

he ultimate sensitivity of a receiver is determined by the noise erated within the receiver itself. Noise voltages are particularly serious in the early stages of a receiver, where the level of signal may be very small. An important design problem is to decide whether a useful purpose is served by placing an r.f. amplifier in front of a receiver which has a crystal mixer as the first stage.

Although the noise performance is the major consideration, an amplifier offers other advantages over a crystal mixer. These are:

(*a*) The problem of reducing local-oscillator radiation, caused by feed-through to the aerial, is simplified. This radiation is reduced by the back-to-front attenuation of the amplifier.

(*b*) Elaborate tuning circuits have to be used with crystal-mixer first stages if good selectivity is to be obtained. This problem is simplified if an r.f. amplifier is used.

(*c*) The overall design of the receiver, for minimum noise factor, is simplified by the inclusion of an r.f. amplifier.

Considering the last point, a receiver with a crystal mixer as the first stage has a noise factor N given by

$$N = L(T + N_{if} - 1)$$

where L = Crystal conversion loss.
T = Crystal noise/temperature ratio.
N_{if} = Noise factor of the i.f. amplifier.

T is normally around 2 and since N_{if} can range from 1·4 (1·5 dB) upwards, at an intermediate frequency of 45 Mc/s the i.f. amplifier makes a substantial contribution to the total noise output. For minimum noise factor, therefore, the first stage of that amplifier has to be carefully designed and a good low-noise valve must be used.

The overall noise factor N of a receiver with an r.f. amplifier placed before the mixer is given by

$$N = N_1 + \frac{N_2 - 1}{G_1}$$

where N_1 = Noise factor of the first stage.
N_2 = Overall noise factor after the first stage.
G_1 = Gain of the first stage.

As an example, typical values may be $N_1 = 12$ dB, $N_2 = 14$ dB and $G_1 = 12$ dB, which gives $N = 12{\cdot}4$ dB. Thus, if the noise contribution of the second and subsequent stages is to be kept below 0·5 dB, it is essential that the gain of the first stage should be 12 dB or better.

Triodes, or triode-connected pentodes, are universally used in the first stage of low-noise receivers at frequencies up to about 250 Mc/s, and an earthed-cathode input stage feeding an earthed-grid stage (known as the cascode circuit) has been found to give the best results.

It is well known that optimum noise factor is obtained by mismatching the input circuit of the first stage.[1] The degree of mismatch required decreases with increase of frequency, and, if the noise factor of the first stage alone is considered, mismatching is effective at frequencies up to around 500 Mc/s, the upper frequency limit depending on the valve type.

itten contributions on papers published without being read at meetings are d for consideration with a view to publication.
e paper is a communication from the Staff of the Research Laboratories of The ral Electric Company, Limited, Wembley, England.

Mismatching, however, is only advantageous in practice if an improvement in the overall noise factor is obtained; thus, under mismatched conditions, the gain of the first stage must still be sufficient to swamp the noise from the rest of the receiver.

Comparing the performance of the cascode amplifier with that of the earthed-grid amplifier, it is worth noting that for optimum noise factor a particular valve type requires the same value of source resistance at the input in both circuit arrangements. In the cascode amplifier, for optimum noise performance the source is coupled more tightly to the input circuit than for matched conditions, whilst with the earthed-grid circuit the coupling is looser. This looser coupling, required in the earthed-grid circuit at frequencies below 300 Mc/s, reduces the gain of the stage to a level where second-stage noise becomes significant, and the overall noise performance is therefore worse than that of the cascode circuit, which has a much higher available gain. At frequencies higher than this, however, where mismatching produces only a little improvement in noise factor, full use is made of the available gain and the earthed-grid circuit is more suitable.

The earthed-grid connection is well adapted for line-circuit operation. This is a great advantage above 300 Mc/s, where lumped-circuit techniques become progressively more difficult.

(3) THEORETICAL ASPECTS OF THE VALVE DESIGN

Circuit considerations affect the design of high-performance valves to a much greater extent than they do with conventional valves. The circuit designer calls for a valve having low noise, high stability and a large gain-bandwidth product. The theoretical methods of achieving these requirements are quite well known,[2] but the valve designer is limited in the extent to which he can apply these principles, owing to the rapidly-increasing manufacturing problems which result.

The noise performance can be improved by reducing the electron transit time, and this is achieved by reducing the grid-cathode clearance to a minimum and by increasing the cathode current-density. At the present time, the only successful alternative to mica for electrode spacing is the use of the envelope, as in disc-seal valves, and for a simple valve the former is the obvious choice. Experience suggested that the smallest grid-cathode clearance which could be maintained with a mica spacer was about 40 microns. This dimension governs the pitch of the grid and also the grid wire diameter; these are 50 and 10 microns respectively. Theoretically the transit time is inversely proportional to the cube root of the cathode current-density, and thus a point is reached when an increase in current density merely increases manufacturing problems without greatly improving the noise performance. With the chosen grid-cathode clearance, it has been found that very little noise improvement is obtained by allowing the cathode current-density to exceed 150 mA/cm^2. Although this is about three times the density in conventional receiving valves with oxide cathodes, a reasonably long life is obtained in disc-seal valves with 300 mA/cm^2. The current density chosen should therefore ensure an adequate life for most applications. In practice, an emitting area of 0·1 cm^2 operating with a current of 15 mA proves a very satisfactory combination. In order to achieve good stability the feedback paths must be reduced to a minimum. Fig. 1 shows the equivalent circuit of a triode at high frequencies, and it can be seen that there are four different feedback paths:

(*a*) The grid-lead inductance, which forms an impedance common to the input and output circuits.
(*b*) The capacitance between anode and cathode.
(*c*) Mutual coupling between the anode lead and the cathode and heater leads.
(*d*) Feedback caused by the flow of anode current through the source; this is present at all frequencies, and is inherent in earthed-grid amplifiers.

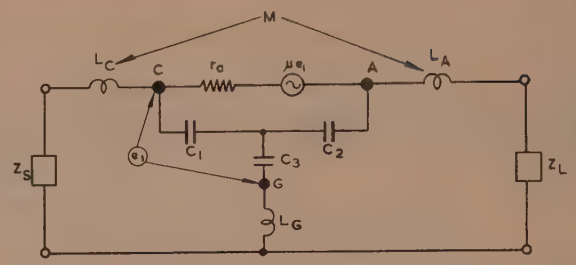


Fig. 1.—Equivalent circuit of a triode at high frequencies.
M = Mutual coupling between anode lead inductance L_A and cathode lead inductance L_C.
L_G = Grid lead inductance.
Z_S = Source impedance.
Z_L = Load impedance.
r_a = Anode resistance of valve.
μ = Amplification factor of valve.
e_1 = R.F. voltage between cathode and grid electrodes.
C_1, C_2, C_3 represent the equivalent T-network of the inter-electrode capacitances.

If a pressed-glass base is to be used, the inherent lead induc tance and inter-lead capacitance within the glass thickness mus be accepted, and the best that can be done is to use as many gri leads as possible and to separate the anode lead from the cathod and heater leads. There is also little that can be done to reduc the feedback in the actual working area of the valve. Th method of connection between the base and the electrodes the becomes of the utmost importance, and has been found to mak all the difference between a valve which becomes unstable a around 500 Mc/s and one which will operate up to abov 1 000 Mc/s.

The third requirement, that of a large gain-bandwidth produc calls for a small output capacitance coupled with a large mutua conductance. The latter will, of course, already have bee achieved by using a small grid-cathode clearance.

On considering the electrode design which would best mee these requirements, it soon became evident that a single-side planar system offered many advantages over a more orthodo double-sided design.

These advantages are:

(*a*) A small emitting area can be obtained while using reasonab cathode dimensions.
(*b*) Inter-electrode capacitances, including direct feedback capac tance, are substantially reduced.
(*c*) The problem of separating the input and output circuits simplified, and the danger of feedback in the circuit is reduced.
(*d*) Slight differences in the geometry of a double-sided syste are inevitable and the resulting unbalance is accentuated durin processing, since the side inclined to draw the most anode curre is activated at the expense of the other side. This becomes seriou in valves with very small clearances. In a single-sided system th effect is absent.

(4) PRACTICAL ASPECTS OF THE DESIGN OF A LOW-NOISE TRIODE

In the A2521, the conventional rectangular box cathode wa chosen as the basis for the design, since the effects of expansio on the grid-cathode clearance would be small and there woul be little risk of distortion during operation.

The form of the grid was dictated by the adoption of a plana electrode system together with the use of wire as fine a 10 microns. The planar type of grid frame, successfully use in disc-seal valves for many years, was easily modified to su the requirements of a mica-spaced valve.

One major requirement of the valve was that it should b simple. This therefore excluded the possibility of adopting on of the several methods of individually adjusting grid-cathod clearances, used in disc-seal valves. The components themselve had to be of sufficient accuracy to ensure a reasonably sma

ead in characteristics. The maximum tolerance which could permitted in grid-cathode clearance was 10 microns, this being sum of individual tolerances on mica, cathode and grid. The ievement of such very close tolerances on components uired the development of new techniques, and these will be cribed by considering each component in turn.

The method of mounting the electrode system on the base found to be of extreme importance, as indicated in Section 3.

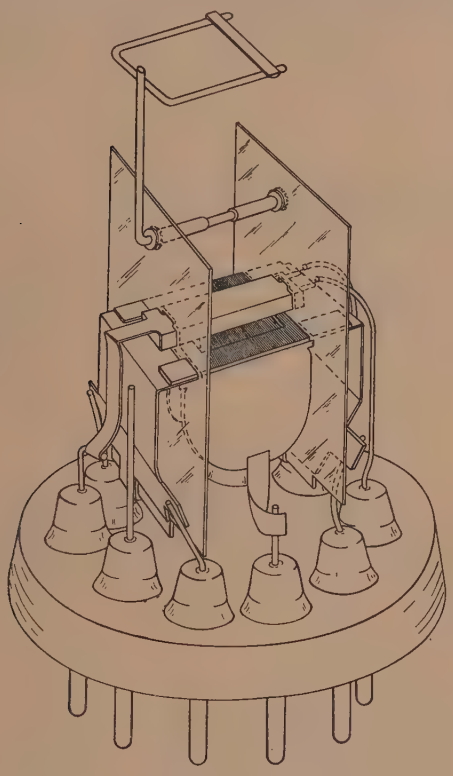


Fig. 2.—The A2521 earthed-grid triode.

final solution is shown in Fig. 2. The grid is mounted izontally and is connected to the base at each end by wide lds, using five base leads.[3]

The important electrode dimensions and spacings are given in ble 1.

Table 1

ELECTRODE DIMENSIONS AND SPACINGS

Grid.	Wire diameter,	10 microns
	Pitch,	50 microns (506 turns per inch)
Cathode.	Active area,	4 mm × 2·5 mm
Spacings.	Grid to cathode,	0·04 mm
	Grid to anode,	0·27 mm

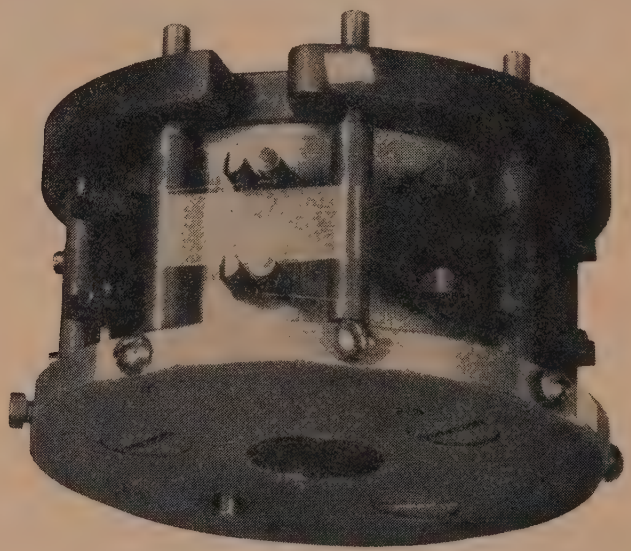
(5) DETAILS OF CONSTRUCTION

(5.1) Grid

The planar grid is constructed by brazing tungsten wires on simple frame punched from molybdenum sheet. The usual hod of making grids of this type is to wind the grids in pairs a special machine, the wires being brazed in position by nacing.[4] The brazing material, which may be gold or copper, ther electroplated on to the frames before winding or painted in suspension form after the wires are in position. An mina-coated molybdenum spacer is usually sandwiched veen the two frames to prevent them brazing together.

his method, although well tried, is necessarily lengthy and well suited to the large-scale production of grids with wire as small as 10 microns in diameter. In addition, it is impossible to achieve the high standard of pitch accuracy which is desirable for a low-noise valve.

A new method of making accurate and cheap planar grids has been developed for this and similar valves, and a paper describing the new technique has recently been published.[5] With this method, an octagonal mandrel is made with an accurately-threaded rod at each corner; the rods are indented to the pitch of the desired grid, and a high standard of pitch accuracy is obtained by means of a 'Merton nut'.[6] This is a flexible nut which is used for transferring the thread from an accurate master on to each of the eight rods; the flexibility in the nut has the effect of averaging out the errors over a large number of turns of the master thread. The mandrel is wound so that successive turns of the wire are located in successive indentations in the threaded rods. The resulting mandrel has eight faces accurately wound to the desired pitch (see Fig. 3). A gold-plated grid



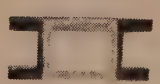


Fig. 3.—Grid brazing mandrel.

frame is then placed over locating pegs on one face of the winding and is brazed in position by eddy-current heating in a reducing atmosphere. The remaining seven positions are treated in the same way, and a string of eight grids can then be removed from the mandrel.

During brazing, the wires across the aperture of the grid are relatively cold, with the result that they become slack when the frame cools. It is therefore necessary to stretch the frame by pressing small indentations simultaneously in both sides of the frame. This leaves the wires with a residual tension of about 40% of their breaking load.

(5.2) Cathode

(5.2.1) Cathode Core.

The conventional box cathode needs specialized treatment to meet the requirements of a small-clearance valve. The minor axis must be held to within very close limits and the faces must be absolutely flat. This is achieved by thoroughly annealing

the cathode and pressing it on to a closely-fitting hardened-steel mandrel; the cathode is then quite soft and requires careful handling during subsequent operations.

(5.2.2) **Cathode Coating.**

It has been found impossible to control accurately the sprayed thickness of the cathode coating. Some subsequent treatment is essential, not only to obtain the correct thickness, but also to give a relatively smooth surface. There are three practicable methods of doing this.

The coating may be rolled, in which case the amount by which the thickness is reduced must be small to avoid disturbing the bond between coating and metal.

A second method is to compress the coating to about one-third of its thickness; this is more suitable for the shell cathodes used in disc-seal valves.

The third method, and the one chosen here, is to scrape away the coating in excess of the required thickness. The jig shown in Fig. 4 was designed for this purpose. Essentially it consists

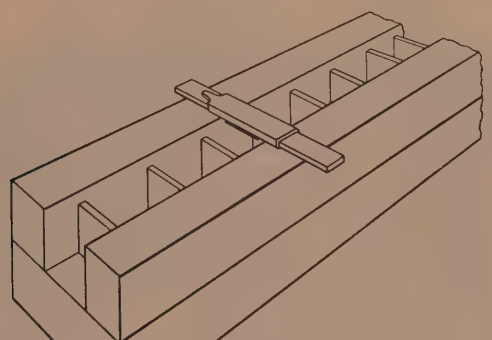


Fig. 4.—Cathode scraping jig.

of two ramps between which are mounted a number of blades which vary uniformly in height along the length of the jig. The cathode is mounted on a mandrel and placed on the jig so that the ramps support the cathode on either side of the coating. When the cathode is drawn along the ramps from one end, each blade removes a predetermined thickness of coating, usually 0·005 mm. The distance travelled along the jig then controls the thickness of coating above the base metal. Downward pressure is exerted through the mandrel, the thickness of which is not important.

The design of jig has a number of advantages, the chief being the simplicity of altering the coating thickness and the fact that the coating is removed in many small steps. The coating which is scraped away falls between the blades and ramps and does not give trouble.

(5.3) Mica

The conventional slotted mica has proved satisfactory as a method of spacing the electrodes of valves for many years. With a clearance as small as 0·04 mm, however, the tolerance on slot spacing becomes very serious. The closest tolerance which can be asked of the toolmaker when making a punch and die is 0·007 mm total; this is almost 20% of the clearance. Fortunately it has been found that a single mica blanking tool, when carefully set up, produces micas to a much closer tolerance. It is thus necessary to segregate batches of micas which have been made with different tools, or even at different times with one tool; slight differences can then be allowed for by adjusting the cathode-coating thickness on the scraping jig.

The optical measurement of slot spacings in micas is unsatis factory owing to the slight bruising which occurs with even th best tools, and it is interesting to note that by far the mos sensitive test of grid-cathode clearance is the measurement o valve characteristics.

(5.4) Anode

The grid-anode spacing is quite large, and wider tolerances ar permissible. The anode therefore consists of a simple channel section formed from thin carbonized nickel. It is located i each mica by two ears, which are on the sides of the channe rather than the front in order to reduce the grid-anod capacitance.

(5.5) Assembly

The open structure of the valve makes it quite suitable fo hand assembly, and in fact a large number of valves have bee made in this way. The advantages to be gained by the use o an assembly jig, however, are considerable, since less skill i required and the speed of the operation can be increased. Th design of an assembly jig has proved a difficult problem, sinc it is essential that the clearance be controlled by the micas an not by the jig.

(6) PERFORMANCE MEASUREMENTS

(6.1) Instability

Instability, which is caused by feedback from the output circu to the input, is a function of the r.f. load resistance in the anod circuit. Any valve can be made stable if the loading is suff ciently heavy, but with conventional valve types in the u.h. range, this has to be so great as to make the gain of the stag very low.

In early experimental valves, where the electrode system wa identical with that of the final design but was mounted verticall on the same base, improved stability was obtained when th number of connections to the grid was successively increase from one to five. With the maximum of 5 grid leads, the valv was unstable at certain critical frequencies in the range 500 900 Mc/s, even when the gain was limited to 8 dB.

In the final design of the valve there was no indication o regeneration at any point up to 1 000 Mc/s, and even when th gain was made to exceed 14 dB, the input circuit still made n contribution to the overall bandwidth.

It is virtually impossible to estimate or measure the separat contributions to feedback produced by the three high-frequenc feedback paths outlined in Section 3. The inherent feedback i earthed-grid amplifiers due to the flow of anode current throug the source can, however, be estimated using low-frequenc theory.

At low frequency the input resistance, R_{IN}, of an earthed-gri amplifier, with the anode circuit tuned, is given by

$$R_{IN} = \frac{r_a + R_L}{\mu + 1}$$

where r_a = Anode resistance of the valve.
R_L = Load resistance.
μ = Amplification factor of the valve.

Taking into account the resistance damping R_e due to transi time effects, and ignoring high-frequency feedback, the inp resistance then becomes

$$R_{IN} = \frac{(r_a + R_L)R_e}{(\mu + 1)R_e + (r_a + R_L)}$$

The input resistance is seen to depend on the load resistanc

hence on the gain of the amplifier, and is less when the ode circuit is short-circuited than when it is tuned.

At high frequency, if excessive feedback is present, anode cuit detuning introduces a negative resistance into the input cuit, thereby making the input resistance greater than when anode circuit is tuned. The way in which the input impece varies with anode tuning therefore gives a good indication the total feedback present. The measured change can be npared with the calculated change, using the low-frequency ory outlined above and substituting a value for R_e appropriate the frequency.

The input impedance variations with anode tuning described closed loops when plotted on a Smith chart. In the absence of high-frequency feedback, the loops should appear above the centre-frequency input impedance. In practice, the size of the loops and the amount by which they appear below the centre-frequency impedance give an estimate of the amount of high-frequency feedback present. If the loops appear wholly below the centre-frequency impedance, the valve is almost certain to oscillate at some point when the anode is detuned.

The measurement of input impedance was made to cover the frequency range 500–900 Mc/s. In the test circuit (see Fig. 5), the input was fed directly on to the cathode. The input impedance had to be measured at the end of the input plug (reference point A) because of the difficulty in establishing a short-circuit reference point at the cathode pin itself. The length of lead *aa'* connecting the cathode to the plug was 1 cm and the transformation produced by this will make the impedance at the cathode pin different from that measured. However, at a particular mean frequency the transformation can be assumed to be a constant over the pass band of the amplifier, in which case the magnitude of the change in input impedance will be comparable at the two points.

In order to keep the input signal-level small during the input impedance measurements, the signal was modulated at 5 kc/s and a high-gain 5 kc/s amplifier was inserted in the probe pick-up circuit. To establish that there were no resonance effects taking place in the input circuit itself, the anode circuit was detuned and input impedance measurements were carried out at 10 Mc/s intervals. The impedance variation is shown dotted in Figs. 6

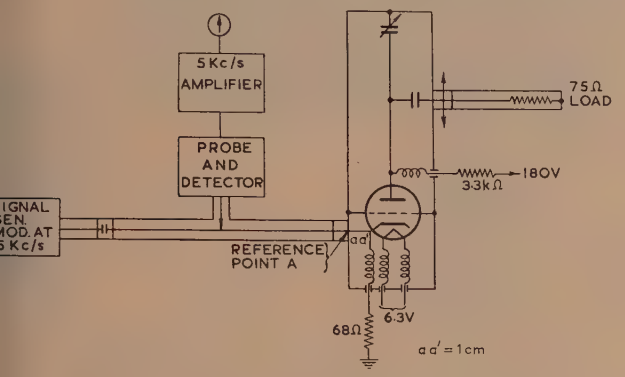


Fig. 5.—Input-impedance measuring equipment.

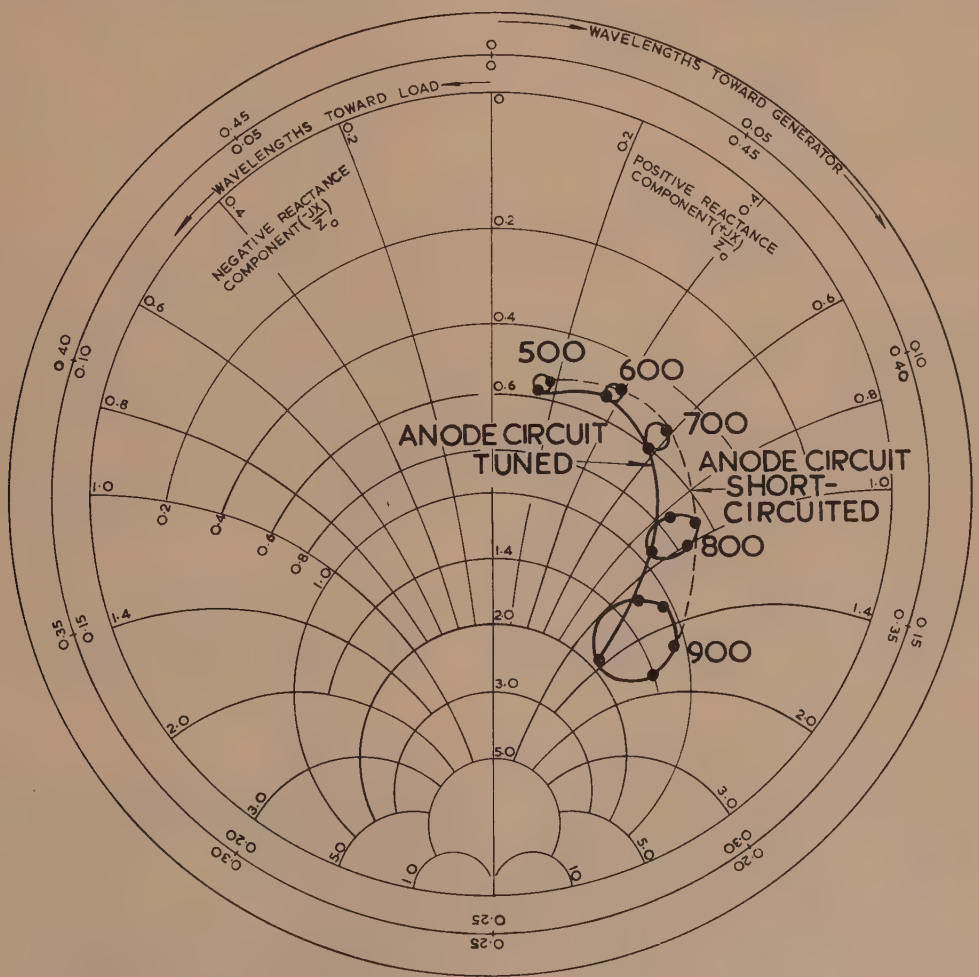


Fig. 6.—Input-impedance variation of the A2521 over the band 500–900 Mc/s with gain fixed at 10 dB.

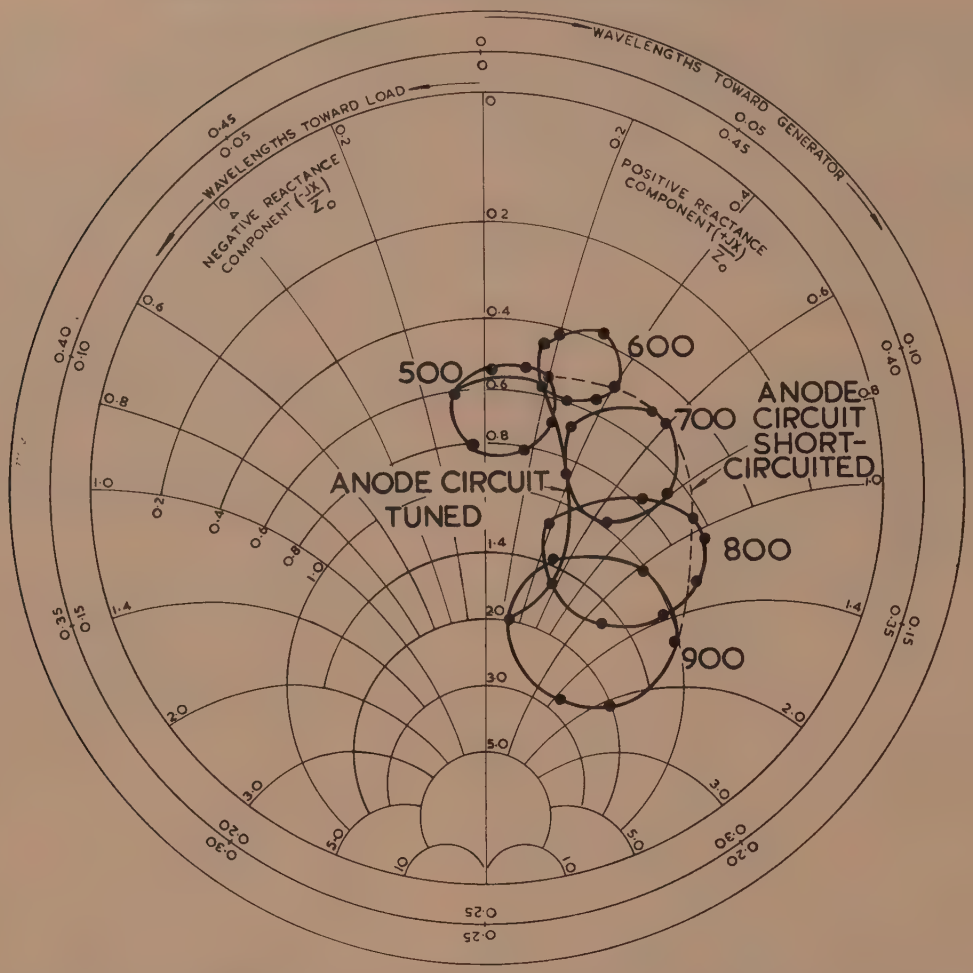


Fig. 7.—Input impedance variation of the A2521 over the band 500–900 Mc/s with gain fixed at 14 dB.

and 7. The absence of any resonance is seen from the regularity of the contour.

Five spot frequencies were taken to check the input-impedance variation as a function of anode tuning; Figs. 6 and 7 show the impedance characteristics obtained when the resonant-frequency gain was fixed at 10 dB and 14 dB respectively.

At the 500 Mc/s end of the band, the sizes of the loops, at both gain levels, are no greater than those estimated from low-frequency theory. The increase in the sizes of the loops at 900 Mc/s shows that feedback is beginning to play a part, but the orientation of the loops is such that very little negative resistance is reflected into the input circuit, and its effect on the operation of the amplifier is still negligible.

The full contours in Figs. 6 and 7 show how the input impedance varies with frequency under tuned-anode conditions. The absence of discontinuities makes it possible to design an input circuit to cover a wide frequency range.

(6.2) Gain-Bandwidth Product

In amplifiers, using line-circuit elements, it is desirable to work on the quarter-wave mode in order to achieve the maximum gain for a given bandwidth. Half-wave or higher mode operation results in considerable loss of gain. However, providing the stage gain is adequate, as explained in Section 2, the noise performance will not be affected by the mode of operation. For best overall performance, the characteristic impedance of the line should lie in the range 50–90 ohms.[7]

Quarter-wave mode operation has an upper frequency-limit determined by the output capacitance of the valve and the len of line inside the valve envelope. In the present valve, with horizontal grid mounting, the anode has been placed underne and the lead length has been reduced to a minimum. Usin line of 90 ohms characteristic impedance the lengths of l external to the valve, obtained when operating in the quar wave mode at 600 and 900 Mc/s, are 5·3 and 1·6 cm respectiv The relatively short length of line at 900 Mc/s limits the maxim attainable bandwidth to 10 Mc/s, but for many applications is sufficient.

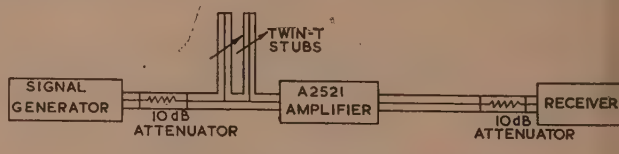


Fig. 8.—Gain-bandwidth measuring equipment.

Fig. 8 is a block diagram of the test equipment. The twi stubs were for input matching, no readjustment being m during bandwidth measurements.

Fig. 9 is a photograph of a quarter-wave line amplifier operation at 600 Mc/s, and Fig. 10 gives a plot of gain ve bandwidth for a typical A2521, run under normal working c ditions, as shown in Table 2. Fig. 11 shows the band pas the amplifier for three nominal gain settings.

In Fig. 12 the performance of the valve in a half-wave circuit at 900 Mc/s is shown. Comparing this with the

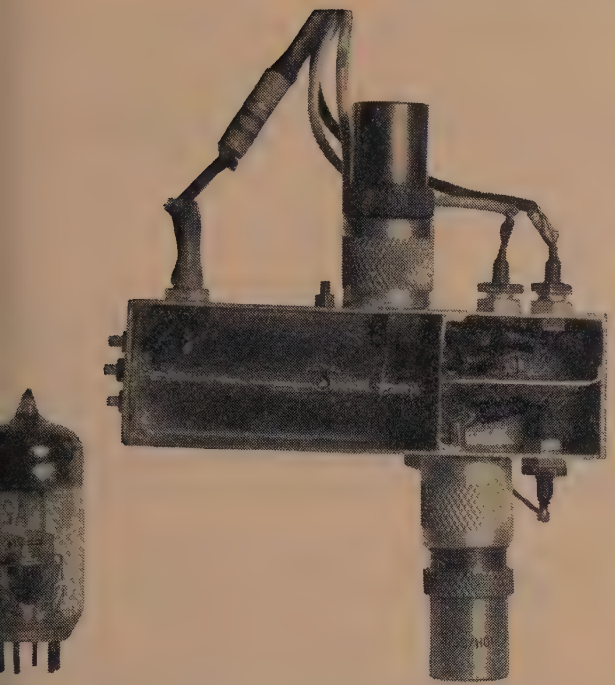


Fig. 9.—Quarter-wave line circuit for operation at 600 Mc/s.

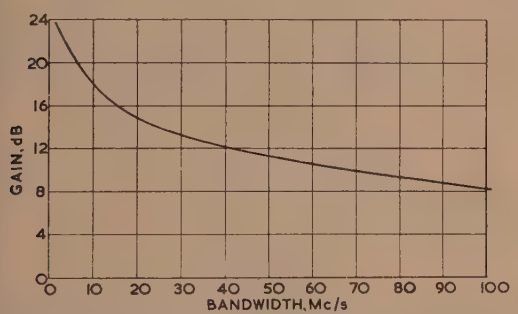


Fig. 10.—Gain versus bandwidth for typical A2521.

Table 2

RUNNING CONDITIONS AND PERFORMANCE

Heater voltage	6·3 volts
Heater current	0·37 amp
Maximum anode voltage	250 volts
Maximum anode dissipation	2·5 watts
Maximum cathode current	20 mA
Maximum heater-cathode voltage	100 volts
Mutual conductance*	15 mA/V
Amplification factor	60

*easured with an h.t. line of 180 volts, an anode series resistor of 3·3 kilohms thode bias resistor of 68 ohms. This gives an anode current of 16 mA in an e valve.

Inter-electrode capacitances

(Measured cold, at 1 Mc/s, with external screen)

$C_{a/g}$	1·6 pF
$C_{a/c+h}$	0·06 pF
$C_{g/c+h}$	3·5 pF

ance in a quarter-wave circuit at 600 Mc/s, it can be seen there is a significant reduction in bandwidth due to the er mode of operation.

(6.3) Noise Factor

lculations of the noise factors of triodes, based on the usual theory,[8] have always given optimistic results, and the noise rs of all valves are therefore measured.

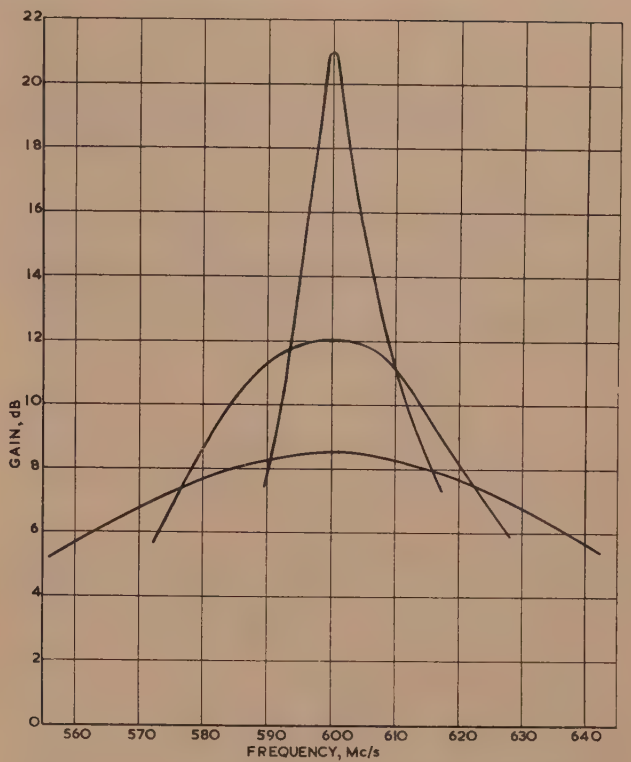


Fig. 11.—Band-pass of A2521 for 3 nominal gain settings.

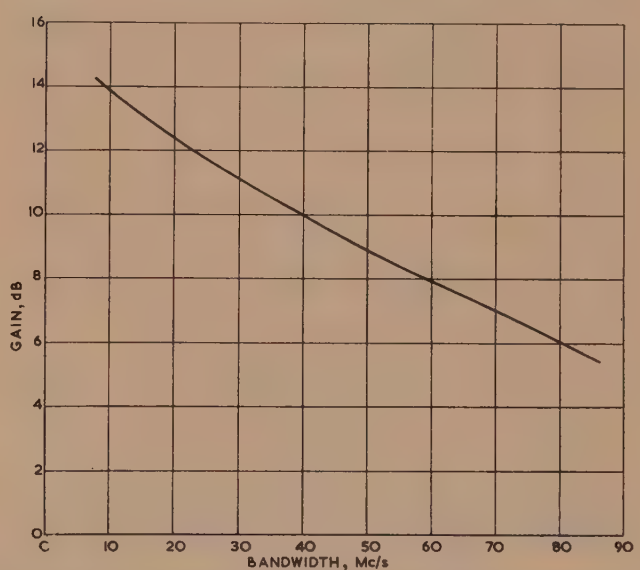


Fig. 12.—Gain versus bandwidth of A2521 in half-wave line circuit at 900 Mc/s.

The measurement is most easily carried out by the use of a temperature-limited diode as a noise source. Diodes mounted on glass bases work satisfactorily at frequencies up to around 250 Mc/s, but at higher frequencies, series-resonance effects caused by the lead inductance and the valve capacitance give optimistic results unless proper precautions are taken. Coaxial diodes, such as the CV2341, suffer less from this defect, but as the frequency is increased, a point is reached where the time of transit of electrons from the cathode to the anode can no longer be neglected. The effect of this is to give a reduction in the noise output. This reduction has been estimated for the CV2341

and the necessary corrections have been applied in all the noise factors quoted in the paper. Discharge-tube noise sources, using a helix to couple the discharge column to the coaxial line, are known to give consistently lower noise factors than temperature-limited diodes. The cause of this discrepancy is not understood. Our measurements at 900 Mc/s have shown the difference to be as much as 2·0 dB.

Noise factor measurements consist in measuring noise powers, and this necessitates accurate calibration of the detector. Two methods have been used to achieve this and the results obtained agree to within ±0·1 dB. A block diagram of the test equipment, illustrating both methods, is shown in Fig. 13, the bandwidth of the i.f. amplifier being 2 Mc/s.

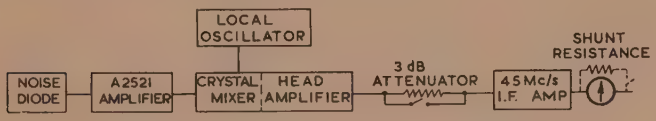


Fig. 13.—Noise factor measuring equipment.

In the first method, a 3 dB attenuator was inserted between the head amplifier and the main amplifier, and the output from the noise source adjusted to give the original output meter reading.

The second method consisted in calibrating a shunt across the output meter. This was done by replacing the head amplifier by a calibrating unit containing two noise sources.[9] Each source consisted of a saturated diode and three amplifying stages, the final stages being coupled to a common output coil. The sources could be switched on independently or together, thereby enabling an accurate doubling to be achieved, and hence calibration of the meter shunt.

Noise factor is critically dependent on the running conditions of the valve, especially if the anode current is made too low or the grid-bias voltage brought too near zero. Fig. 14 shows a

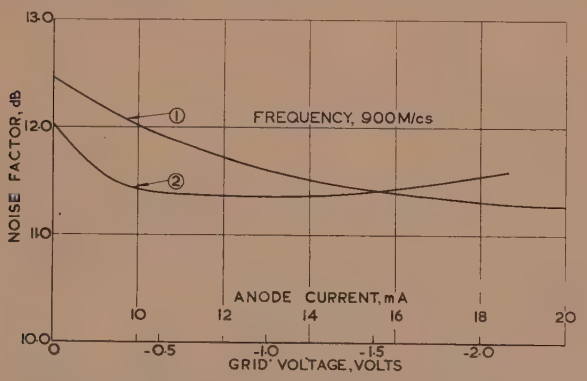


Fig. 14.—Noise factor versus anode current and grid bias.

1. Noise-factor/anode-current at constant grid voltage of −1·0 volt.
2. Noise-factor/grid-voltage at constant anode current of 15 mA.

Noise factor was measured in line circuits using a CV2341 coaxial diode as a noise source.

plot of overall noise factor versus anode current and grid bias for a typical valve. Fig. 15 gives the variation of overall noise factor with frequency under optimum operating conditions.

(6.4) Oscillator Applications

Operating as a Colpitt oscillator, where the tuned circuit is connected between grid and anode and where the potential divider for the cathode drive is provided by the inter-electrode capacitances, the valve has been made to oscillate up to 1 350 Mc/s.

With the anode and cathode well screened from one another, it is then necessary to apply external feedback; this has the advantage that optimum conditions are much more easily realized.

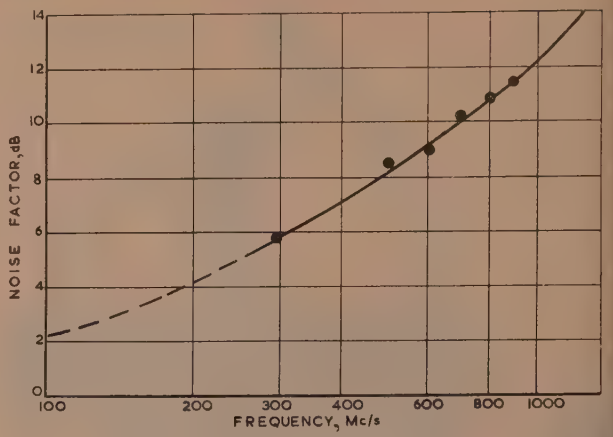


Fig. 15.—Noise factor versus frequency.

Noise factor was measured in line circuits using a CV2341 coaxial diode as a noi source.

The valve gives useful powers for such applications as loc oscillators, the power output at 1 250 Mc/s being 150 mW.

(7) CONCLUSION

A valve of the type described extends the useful range of glas base valves. Its performance as a low-noise amplifier up 1 000 Mc/s is only slightly inferior to that of disc-seal valve and is as good as or better than that of current crystal mixer

The basic electrode system has been used, with a different lea arrangement, in valves for other applications, such as low-noi cascode amplifiers, for frequencies up to 300 Mc/s.

(8) ACKNOWLEDGMENTS

The authors are indebted to the M.-O. Valve Compan Limited for permission to publish this work.

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RADIO-FREQUENCY ASPECTS OF ELECTRO-NUCLEAR ACCELERATORS

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(*The paper was first received* 23*rd April and in revised form* 6*th September*, 1958.)

SUMMARY

he paper gives an account of the various forms of electro-nuclear chines for the acceleration of charged particles, emphasis being on the radio-frequency aspects of the design and performance. an introduction, particle electrodynamics and the original d.c. and accelerators are examined. Linear accelerators in resonant and elling-wave circuit form are then described. Orbital or cyclic chines, with both constant and time-varying magnetic fields, are sidered, and the survey concludes with a bibliography of published rmation.

LIST OF PRINCIPAL SYMBOLS

c = Velocity of light *in vacuo*, 3×10^{10} cm/sec.
e = Charge on electron, coulomb.
E = Accelerating electric field, volts/cm.
E_0 = Axial accelerating electric field, volts/cm.
f = Frequency, c/s.
F = Force exerted on particle, dynes.
H = Magnetic field intensity, oersteds.
m = Equivalent mass of particle, grammes.
m_0 = Rest mass of particle, grammes.
p = Momentum of particle, grammes cm/sec.
P = Power, watts.
P_m = Power dissipated in cavity, watts.
P_0 = Power dissipated per unit length of accelerator, watts/m.
r = Radius of particle orbit, cm.
R = Shunt resistance of cavity referred to gap
$= 10^{-6}V_g^2/2P_m$ megohms.
t = Time, sec.
v = Velocity of particle, cm/sec.
v_g = Group velocity of wave, cm/sec.
V = Voltage, volts.
V_g = Maximum gap voltage, volts.
W = Total energy, ergs or electron-volts.
W_k = Kinetic energy, ergs or electron-volts.
W_0 = Rest energy of particle, ergs or electron-volts
$= m_0c^2$.
z = Linear position of particle, cm.
Z_s = Shunt impedance per unit length of accelerator
$= E_0^2/P_0$ megohm/m.
λ = Free-space wavelength, cm.
σ = Conductivity of material
$= 5{\cdot}8 \times 10^5$ mhos/cm. for copper.

(1) TYPES OF ACCELERATOR

(1.1) Particle Electrodynamics

aboratory-controlled intense sources of high-energy charged ticles are required to an increasing extent in modern nuclear nce and technology,[27] for applications in the medical field[24] , in some instances, for the generation of power at millimetre elengths.[31] This need has led to the development of a ety of accelerating machines whose operation depends upon energy relations of charged particles moving in electric and magnetic fields.

It has been shown by, for example, Shamos and Murphy[150] and Livingston[98, 99] that, when in motion, a particle has a total energy given by

$$W = mc^2 = W_0 + W_k = m_0c^2 + W_k \quad . \quad . \quad (1)$$

The equivalent mass is given by

$$m = m_0 + W_k/c^2 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In particle accelerators the kinetic energy results from the force exerted on the particle by an electric field. Since this force may be expressed as the time rate of change of momentum,

$$F = dp/dt = d(mv)/dt = mdv/dt + vdm/dt \quad . \quad . \quad (3)$$

and, since force times distance is change in kinetic energy,

$$Fdz/dt = Fv = dW_k/dt = c^2dm/dt \quad . \quad . \quad . \quad (4)$$

From eqns. (3) and (4)

$$vdp/dt = dW/dt \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

which, on multiplying by $m = W/c^2$, gives

$$mvdp/dt = pdp/dt = (W/c^2)dW/dt \quad . \quad . \quad . \quad (6)$$

Integration of eqn. (6) gives

$$\tfrac{1}{2}p^2 = \tfrac{1}{2}m^2v^2 = \tfrac{1}{2}(W^2 - W_0^2)/c^2 \quad . \quad . \quad . \quad (7)$$

whence, on substitution of W from eqn. (1),

$$p = [W_k(2W_0 + W_k)]^{1/2}/c \quad . \quad . \quad . \quad . \quad (8)$$

For the classical case of $W_k \ll W_0$, eqn. (8) becomes

$$W_k = \tfrac{1}{2}p^2/m_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

giving the usual quadratic relation between kinetic energy and momentum. For the relativistic case of $W_k \gg W_0$, eqn. (8) becomes

$$p \simeq W_k/c \quad . \quad . \quad . \quad . \quad . \quad (10)$$

giving a linear relation between kinetic energy and momentum. If v is expressed as a fraction of the velocity of light, eqn. (7) gives

$$m^2v^2 = (W^2 - W_0^2)/c^2 = c^2(m^2 - m_0^2) \quad . \quad . \quad (11)$$

whence

$$m/m_0 = W/W_0 = [1 - (v/c)^2]^{-1/2} \quad . \quad . \quad (12)$$

Eqn. (12) shows that the mass of the particle increases appreciably only at very high velocities. Particle energies are usually expressed in electron-volts and Table 1 gives data for five types of particles.

Eqn. (7) gives the relation

$$v/c = [1 - (W_0/W)^2]^{1/2} = [1 - 1/(1 + W_k/W_0)^2]^{1/2} \quad (13)$$

which is plotted in Fig. 1(*a*) as a function of W_k/W_0. The abscissa is also expressed in terms of the kinetic energy of the electron and proton. It is seen that the velocity of light is

ritten contributions on papers published without being read at meetings are ed for consideration with a view to publication.
. Harvey is at the Royal Radar Establishment.

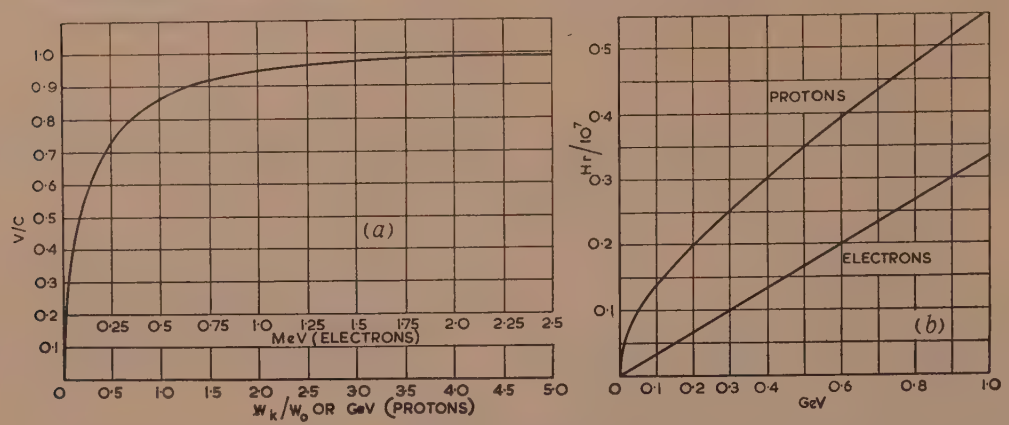


Fig. 1.—Energy of accelerated particles.

(*a*) Values of v/c are plotted as functions of kinetic energy, W_k, measured in electron-volts and units of W_0.
(*b*) Hr as a function of kinetic energy for protons and electrons.

Table 1

PARTICLE DATA

Type of particle	Charge	Rest energy	Kinetic energy for $m=1{\cdot}01\,m_0$
	e	MeV	MeV
Electron ..	1	0·51	0·005
Proton ..	1	938	10
Deuteron ..	1	1 876	20
Triton ..	1	2 814	30
Alpha ..	2	3 752	40

closely approached by electrons of a few mega-electron-volts and by protons of a few giga-electron-volts.

Accelerating machines often require a particle to travel in a circular orbit. Such a motion can be achieved by a radial electric field, but since electromagnetic forces are much greater than electrostatic ones, a guiding magnetic field is generally employed. In this case the charged particle experiences a force perpendicular to the directions of the magnetic field and its own motion given by

$$F' = Hev \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

This force deflects the particle in a circular path whose radius is given by

$$r = mv^2/F' \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

Eqns. (7), (14) and (15) give

$$\begin{aligned} Hr &= (W^2 - W_0^2)^{1/2}/ec \\ &= [W_k(W_k + 2W_0)]^{1/2}/ec \quad . \quad (16) \end{aligned}$$

which, for the classical case, reduces to

$$\begin{aligned} Hr &= (2W_0W_k)^{1/2}/ec \\ &= (2m_0W_k)^{1/2}/e \quad . \quad . \quad (17) \end{aligned}$$

and, for the relativistic case,

$$Hr = W/ec = W_k/ec \quad . \quad . \quad (18)$$

The value of Hr in eqn. (16) is plotted in Fig. 1(*b*) as a function of kinetic energy for protons and electrons. In a uniform magnetic field the particle revolves in a circular orbit at a frequency given by

$$\begin{aligned} f &= v/2\pi r \\ &= Hec^2/[2\pi(W_0 + W_k)] \quad . \quad (19) \end{aligned}$$

which, in the classical case, becomes the well-known value of $He/(2\pi m)$.

(1.2) Low-Frequency Accelerators

The simplest accelerators use constant-potential sources suc as the Cockcroft–Walton[28] circuit or, as in the example show in Fig. 2(*a*), a Van de Graaff[163, 164] generator. This type generator establishes a potential difference by mechanical transferring electrostatic charges between points through th medium of a non-conducting belt driven by a motor. Charg is sprayed on to the belt from needle points raised to a potenti of several kilovolts. On arriving inside the hollow metal ele trode at the opposite end of the belt arrangement, the charge removed by a second electrode and passes to the outside of th sphere and raises its potential.

The particles are accelerated inside a highly evacuated tub with a particle source at one end and a target at the other, multiple-electrode structure distributing the accelerating fie uniformly along the tube. Energies up to several mega-electron volts are achievable, but it is then necessary to enclose th complete generator and accelerator unit in a pressurized tan Accelerators built along these lines give a relatively high bea density and a very narrow energy spectrum but have the disa vantage of requiring insulation for a voltage equal to the desire particle energy.

Higher energies were obtained by Wideroe[172] using synchro nous acceleration in an alternating field. This principle w later developed by Lawrence and Sloan,[92] who accelerate mercury ions to 2·85 MeV by passing them, as shown in Fig. 2(*b*

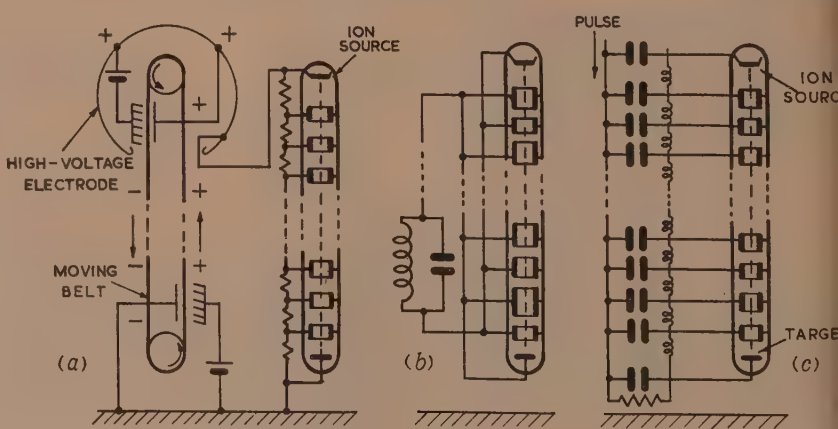


Fig. 2.—D.C. and l.f. linear accelerators.

(*a*) Rotating-belt Van de Graaff accelerator.
(*b*) Tuned-circuit Sloan and Lawrence accelerator.
(*c*) Travelling-wave Beams and Snoddy type.

ough a series of cylindrical electrodes connected to opposite minals of an alternating-potential source. With the proper ationship between electrode length, particle velocity and radio quency, a particle can be accelerated by a given gap, drift ough the field-free region inside the next electrode and arrive the following gap a half-cycle later to be accelerated again, d so on.

In the linear accelerator employed by Beams and Snoddy[9] e electrodes were connected to appropriate points on a loaded nsmission line, as shown in Fig. 2(*c*), to which an impulse ltage was applied. By arranging the times of propagation of e pulse along the line sections to be the same as the transit nes of the particles through the system of electrodes, the rticles were continuously accelerated.

(2) LINEAR ACCELERATORS USING CAVITIES

(2.1) Single Cavity

Accelerating machines of high output and particle energy nploy frequencies in the microwave region. In considering ngle-cavity electron accelerators, Akeley[1,2] showed that the aximum transit time which may be usefully employed constitutes one half-cycle of the r.f. oscillation. For relativistic ctrons exact calculation gives the optimum length of the celerating gap as $0{\cdot}44\lambda$. The emergent electrons will have eir energy increased by an amount equal to the average value voltage during their transit. The maximum increase of ergy is given approximately by

$$(2/\pi)V_g = (2/\pi)(E\lambda/2) = E\lambda/\pi \quad . \quad . \quad . \quad (20)$$

ne power necessary to give this maximum electron-energy crease is given by

$$P_m = V_g^2/2R = (2V_g/\pi)^2/\lambda^{1/2} \quad . \quad . \quad . \quad (21)$$

the case of a circular TM_{01} mode cavity of copper, which, for length $\lambda/2$, has a value R of $1{\cdot}25\lambda^{1/2}$ megohm. In practice E limited to about 5×10^5 V/cm by field emission from the nductors.

A number of single-cavity electron accelerators have been conructed,[18, 65, 66, 135, 155] and a typical assembly, due to Mills,[112] shown in Fig. 3. The r.f. input was from a magnetron nerator giving 600 kW peak power in 5 microsec pulses with a petition rate of 200 c/s. A high-current electron gun, supplied a 10 kV source, directed an electron beam across the accelerag gap when the r.f. voltage was at a maximum value. To sure stable operation of the generator the coupling line was osen to be an optimum length while about one-half the power is dissipated in a water load. The copper cavity had a Q-factor of 12 000 and shunt resistance of 2·7 megohms. In operation the accelerator gave a mean beam current of 70 μA with a maximum energy of 1·2 MeV.

Coleman[31, 85] employed a single TM_{010}-mode cavity at 2·8 Gc/s which was driven by two magnetrons via independent coupling apertures. For a total input power of 800 kW the maximum energy was 1·5 MeV. A prebunching cavity was employed to inject the electrons into the accelerating cavity with the proper velocity and at the correct r.f. phase angle to ensure a high-power bunched output. Skellet[151] has proposed multiple transit as a means of increasing the electron energy. A series of electrodes were connected to a resistance chain so that the static potential distribution was parabolic. The particles follow a simple harmonic motion in this field and gain energy at every transit across the accelerating gap if the r.f. field is synchronized to this motion.

(2.2) Multiple Cavities

If the available r.f. power is distributed among N cavities with the proper phasing, the final energy attained by the accelerated electrons is increased over that given by a single cavity by $N^{1/2}$ up to values of N where attenuation becomes important. To ensure continuous acceleration of relativistic electrons the cavities must be excited with a phase difference of 180°. The cavities may, for example, be fed from a master waveguide by a series of T-junctions via independent phase-changers such as dielectric rods. Stability of generator frequency can be achieved by dissipating[119] a third or a half of the power in a dummy load or by employing separate power amplifiers driven from a master oscillator. In order to provide optimum transit conditions the cavities are usually of a re-entrant nature.

As an example of multiple-cavity design the folded-guide construction employed by Harvey[56] and shown in Fig. 4 will be considered. The accelerating field assumed was 125 kV/cm, so that with a gap length of 2 cm (0·79 in) an increase of energy of 0·25 MeV was obtained. The entrance velocity at A from the 25 kV electron gun was $0{\cdot}32c$, so that the exit velocity from the first cavity at B was $0{\cdot}75c$ (energy 275 keV). With a frequency of 3 Gc/s the transit time was 0·38 cycle. Thus the transit time from B to C was made 0·12 cycle in order that the electrons entered the gap CD in the correct phase. Since the velocity of the electrons along the path BC was $0{\cdot}75c$, the distance BC became 0·36 in. Similarly the velocity at D was $0{\cdot}81c$ (energy 525 keV) giving a distance DE of 0·80 in. The velocity at F was now $0{\cdot}87c$ (energy 775 keV) giving a distance FG of 0·88 in. Finally the exit velocity at H was $0{\cdot}9c$ (energy 1 025 keV) giving a gap transit time of 0·22 cycle. In order to satisfy the phase sequence the electrical length along the waveguide between the

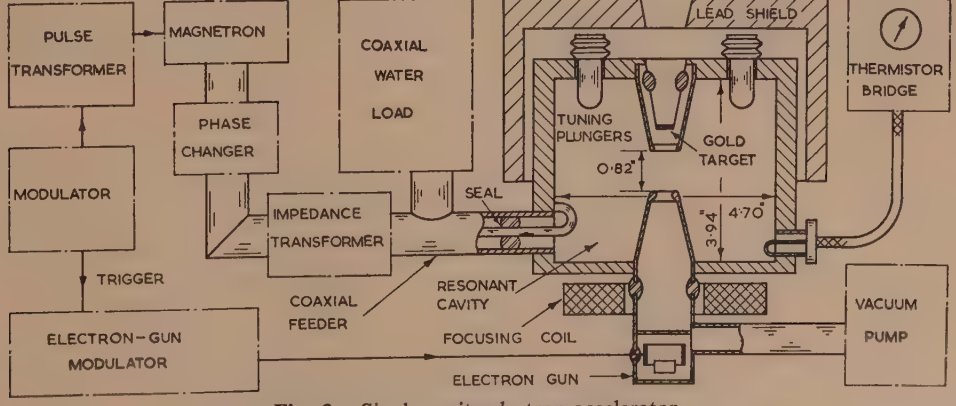


Fig. 3.—Single-cavity electron accelerator.
Operating frequency, 1·2 Gc/s. Output, 1·2 MeV at 70 μA mean beam current.

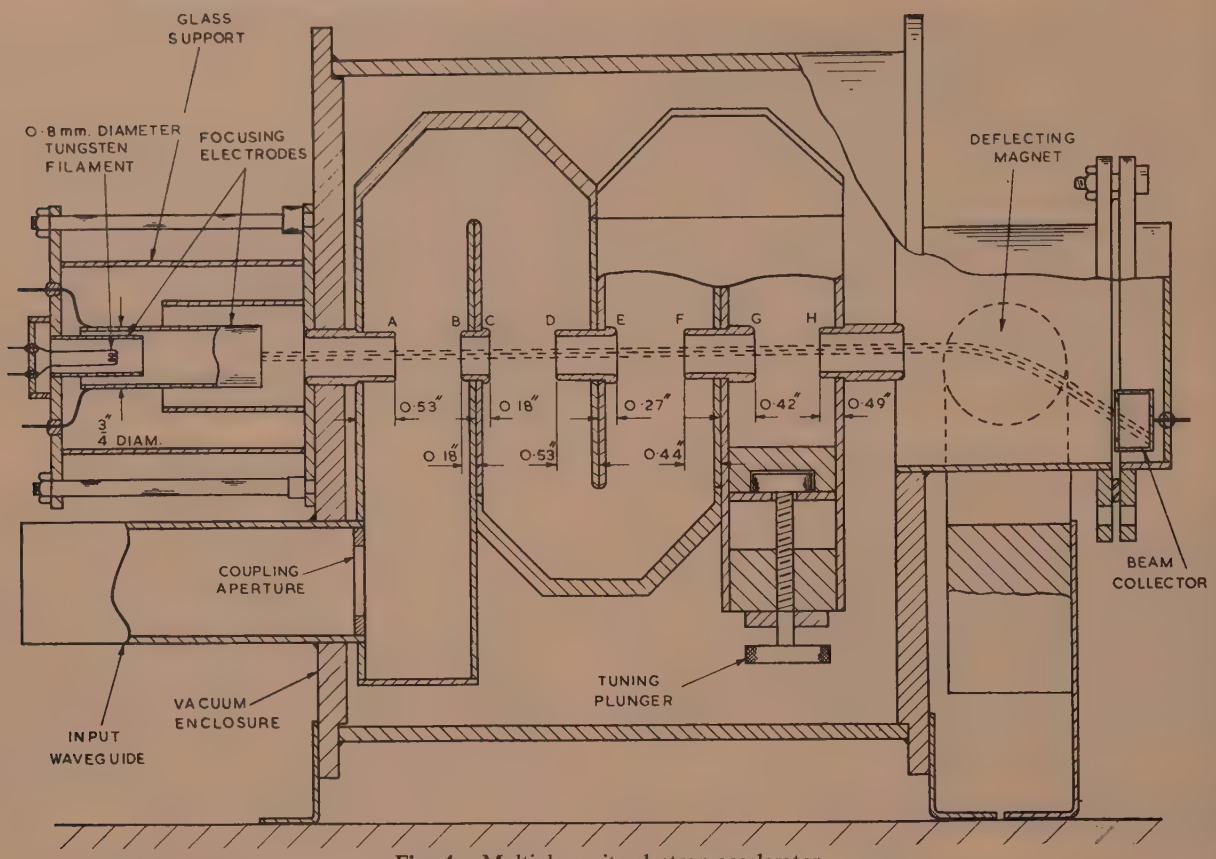


Fig. 4.—Multiple-cavity electron accelerator.

Operating frequency, 3 Gc/s. Power input, 2·5 MW. Output, 1 MeV. Size of waveguide, 2·84 in × 1·34 in internal dimensions. Gap lengths, all 0·79 in. Gun voltage, 25 kV.

gaps was 360°, allowance being made for the phase change of 180° due to folding. With a shunt resistance of 0·5 megohm for each of the eight half-wavelength sections of waveguide, the power required was about 500 kW. The whole assembly was enclosed in a vacuum-tight enclosure.

A number of different arrangements of cavities have been employed for the acceleration of electrons. According to their design, they differ in such practical details as dispersion, build-up time, efficiency, moding, coupling adjustment and manufacturing cost. It is probably reasonable to say that, for the acceleration of electrons to high energies, multiple-cavity structures have been superseded by other means. Electrical details of typical electron accelerators are given in Table 2.

Multiple cavities have been employed for the acceleration of light particles such as protons. Owing to the low velocity of the protons, drift tubes must be provided to shield the particle from the r.f. field when it is in the wrong phase. A typi structure, shown in Fig. 5(*a*), is many feet long and may considered as a series of doubly re-entrant symmetrical caviti as shown in Fig. 5(*b*), repeatedly excited in such a phase that t currents flowing on opposite sides of the joining faces AB canc

The whole structure is resonant in the TM_{010} mode, and desi data by Oppenheimer, Johnston and Richman[125] are included Fig. 5(*c*), dimensional ratios being given to permit easy scali to the desired wavelength. These data can be fitted by t empirical relation

$$(g/L) = 1{\cdot}63(D/\lambda) + 1{\cdot}096(L/\lambda) + 3{\cdot}58(d/\lambda) - 1{\cdot}271 \quad (2$$

It is well known that such structures possess a number of possi resonances, the frequency for a mode number n being given

$$f_n = f_0[1 + (nc/2f_0L)^2]^{1/2} \quad . \quad . \quad . \quad (3$$

Table 2

MULTIPLE-CAVITY ELECTRON ACCELERATORS

Description by	Type of structure	N	Frequency	Input power	Output	
					Energy	Current
			Gc/s	MW	MeV	μA
Allen and Symonds[3]	Cavity	3	3·0	—	—	—
Miller[107]	Cavity	5	3·0	1·0 (3 μsec at 100 c/s)	1·5	0·25
Schultz *et al.*[145,146]	Cavity	8	0·58	—	10	—
Hudspeth[69]	Spiral guide	10	—	—	—	—
Cullen and Greig[34]	Folded guide	3	2·8	0·25	0·3	—

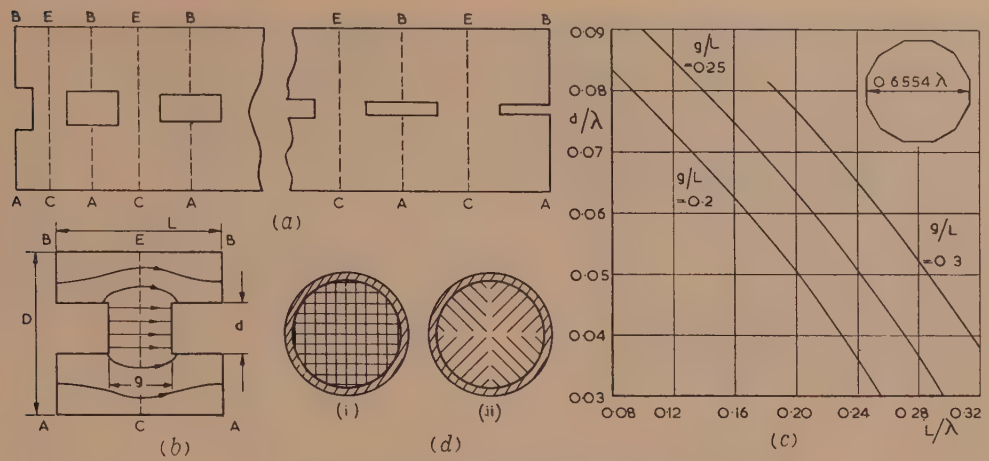


Fig. 5.—Single-cavity proton accelerator.
The cavity increases the energy of protons from 4 MeV to 31·5 MeV.
(*a*) Section of the cavity and drift tubes. (*c*) Design data.
(*b*) Unit cell. (*d*) Two types of grid.

ere f_0 is the frequency of the wanted $n = 0$ mode. For a ıcture 40 ft in length and $f_0 = 200$ Mc/s, the separation from nearest interfering $n = 1$ mode is only 0·17%. To ensure urate manufacture the correct dimensional tolerances have n derived[127] by perturbation theory. Radial focusing and ıse stability are achieved in proton accelerators by arranging ds, of which two types are shown in Fig. 5(*d*), across the rance ends of the drift tubes so that the r.f. electric field lines minate within the beam.

Several multiple-cavity proton accelerators have been con-ıcted, since they have the advantages of relatively large output rent and easy extraction of the beam. According to the size he equipment, the protons are given an initial energy of, say, kV from a Cockcroft–Walton generator to, say, 4 MeV from Van de Graaff generator. A typical beam diameter is 1 cm, h an angular divergence of 10^{-3} radian, and one source of power consisted[175] of 26 units, each consisting of four alleled triodes giving 85 kW. Electrical data on some ctical machines are given in Table 3, the frequency in all es being 200 Mc/s.

(3) TRAVELLING-WAVE LINEAR ACCELERATORS

(3.1) Use of Slow-Wave Structures

n the travelling-wave linear accelerator the r.f. power is fed o one end of a slow-wave structure and is dissipated in the ls as it propagates along the line, the accelerating field being enuated exponentially. Possible types of slow-wave structure lude stub-loaded rectangular waveguides and coaxial lines,[156] most electron accelerators employ the iris-loaded circular de shown in Fig. 6(*a*), the TM_{01} mode providing an axial electric field. Such a structures is well known to possess a low-frequency cut-off due to the waveguide and a high-frequency cut-off at the π-mode when adjacent cavities oscillate in anti-phase. Slater[152, 153] showed that the phase velocity within the pass-band can be controlled by varying either the radius of the iris aperture or that of the waveguide. An accurate expression for the phase velocity in structures in which $n > 5$, n being the number of irises per free-space wavelength, has been obtained by Walkinshaw[170] and checked experimentally by Mullet and Loach.[118] These and other results[48, 159] give, subject to certain assumptions, an upper limit to the energy which a relativistic particle can obtain from such a system when n is between 3 and 4.

The characteristics of linear electron accelerators have been discussed by R-Shersby-Harvie[57] and Fry *et al.*,[42, 43, 44, 45] who show that, for output energy of the particles, a useful figure of merit of slow-wave structures is the shunt impedance[22] given by

$$Z_s = 3\cdot3(\sigma/\lambda)^{1/2}[\sin(\pi/n)/(\pi/n)]^2/(n + 2\cdot62) \quad . \quad (24)$$

For example, if $n = 3\cdot5$ and $\lambda = 10$ cm, Z_s becomes 100 megohm/m, so that a power of 1 MW fed into an accelerator of length 100 m would produce particles of 100 MeV energy. When the size of the iris aperture is fixed, and this is usually just sufficient to allow the passage of the beam, there is an upper limit to the length of structure which may be used without loss of energy due to attenuation. This length is that in which approximately 90% of the power is dissipated in the guide walls and 10% passes out of the end into a matched load. Some data on attenuation are given in Fig. 6(*b*). When the outer diameter of the corrugations is adjusted to give a phase velocity equal to that of light and the frequency is 3 Gc/s then, for iris radii of 2·4 and 6 cm the attenuation-limited lengths are 3·5,

Table 3

MULTIPLE-CAVITY PROTON ACCELERATORS

Description by	Length of structure	Input			Output	
		Power	Pulse length	Repetition rate	Energy	Mean current
	ft	MW	μsec	c/s	MeV	μA
Alvarez *et al.*[4,5]	40	2·2	600	15	31·5	0·4
Cork[32]	18	0·5	—	—	9·9	3 000 (peak)
Day *et al.*[35]	18 + 40 + 40	0·6, 2·2 or 3·2	200	60	10, 40 or 68	0·1

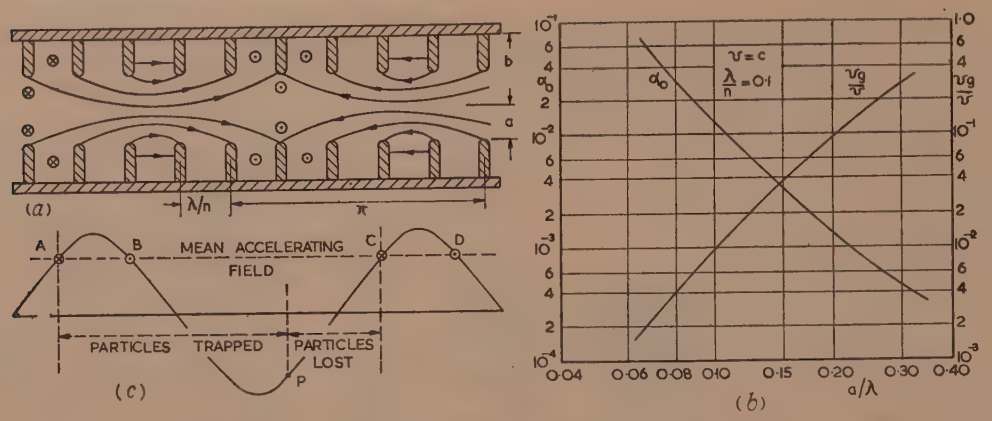


Fig. 6.—Data for TM_{01}-mode linear accelerator.

(*a*) Fields in an iris loaded guide.
(*b*) Attenuation constant $\alpha = \alpha_0\lambda^{-3/2}$ for copper and the group velocity v_g.
(*c*) Phase focusing of particles.
⊙ Stable equilibrium.
⊗ Unstable equilibrium.

40 and 130 metres respectively when five cavities per wavelength are assumed, corresponding to effective shunt impedances of 180, 1 400 and 3 000 megohms. A useful theoretical relation for structures of practical interest giving[170] the axial accelerating field in terms of the power P flowing along the line, for a phase velocity equal to c, is

$$E_0 = 2190P^{1/2}\lambda/\pi a^2 \quad . \quad . \quad . \quad . \quad (25)$$

where a is the iris radius in cm.

In order that the particles should travel in compact bunches in a linear accelerator there must exist axial and radial stability. Fig. 6(*c*) shows that particles injected at the correct phase will gain energy continuously from the r.f. fields, provided, of course, that the phase velocity and particle velocity are the same. Thus the linear accelerator tends to form and maintain electron bunches. The electrons also tend to diffuse radially, and this i countered by a steady longitudinal magnetic field. Radia focusing is helped considerably when very high energies ar reached. If the electron system is taken as a reference with th particle mass constant, the accelerator is foreshortened by factor up to, say, 1 000: the transverse dimensions are, of cours relativistically unaltered. Some improvement can be obtaine by prebunching[128, 129, 130, 131] the electron beam prior t injection.

For high energies it becomes more economical to divide th accelerator in sections, each being supplied from its own ind vidual generator. The usual r.f. source is a klystron amplifie delivering 20 MW in pulses of 2 microsec duration at 60 c/s. typical arrangement is shown in Fig. 7, and, with the grou velocities usually employed, a time of about 1 microsec is require

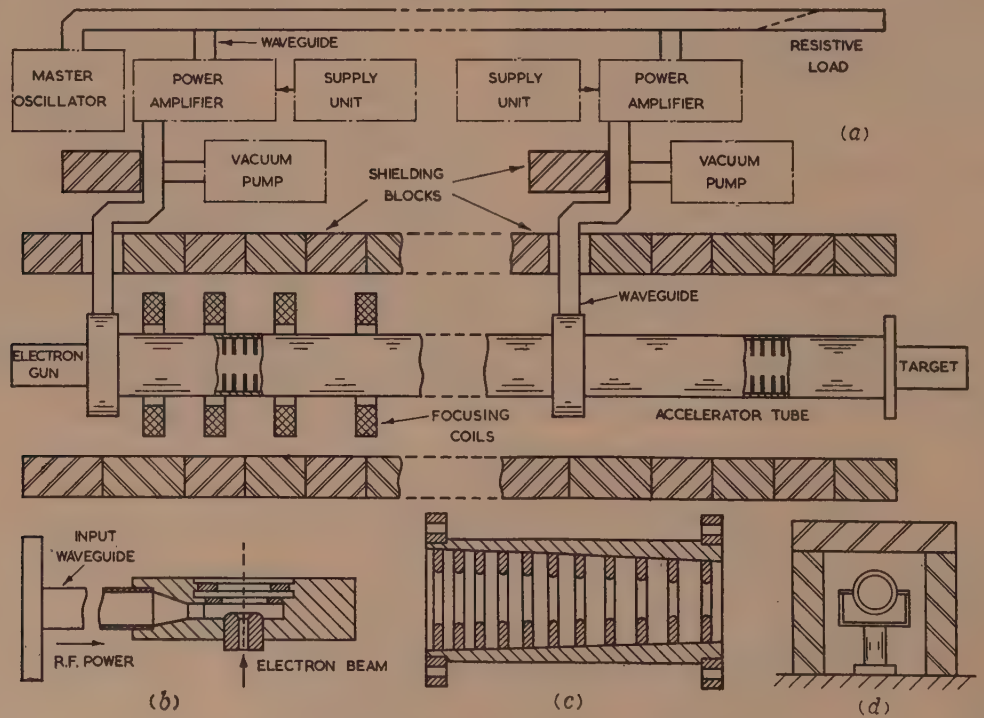


Fig. 7.—Typical travelling-wave electron accelerator.

(*a*) First and last sections of a multiple-unit linear accelerator.
(*b*) Coupling from rectangular to corrugated waveguide.
(*c*) First buncher assembly.
(*d*) Section of the radiation shielding.

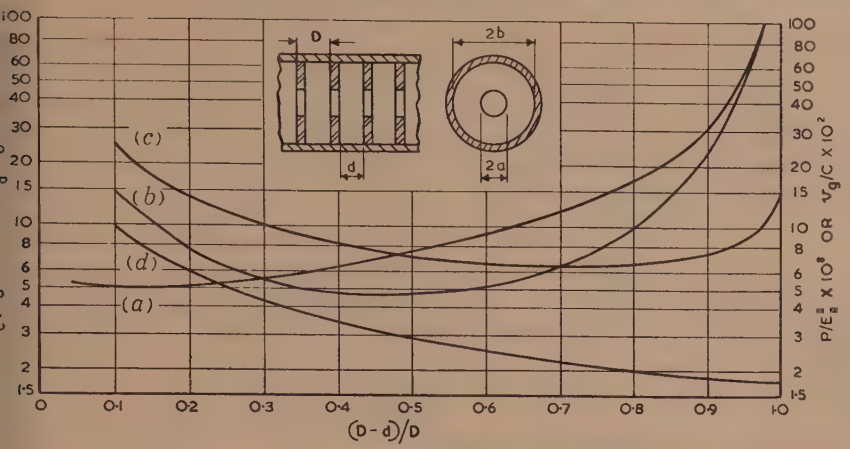


Fig. 8.—Data for anisotropic-dielectric-loaded accelerator.

(*a*) Metal losses. (*c*) Series conductance.
(*b*) Dielectric losses. (*d*) Group velocity.

fill each section with r.f. energy. The iris discs are accurately ound and shrunk into position in the waveguide sections. r a guide of 3·261 in internal diameter, suitable irises would 0·239 in thick with a central hole of rounded contour 0·872 in meter spaced 1·033 in apart. Linear accelerators for very h energies must be quite long. For an accelerating field of 0 kV/cm, a length of 670 m is necessary to give 10 GeV, and ious difficulties are encountered in the manufacture of the veguide to the accuracy required and in the maintenance of correct phase relationships of the generators. A number of ctron travelling-wave linear accelerators have been con-ucted,[7, 68, 97, 166, 167] and typical data are given in Table 4, frequency being 2·8–3·0 Gc/s in all cases.

Table 4

TRAVELLING-WAVE LINEAR ELECTRON ACCELERATORS

Description by	Length	Input		Output	
		Power	Duty cycle	Energy	Mean current
	ft	MW	×10−6	MeV	μA
ry and Walkinshaw[44]	6	2·0	400	4·0	60
hick and Miller[24] ..	25	6 × 6·0	1 500	25	1 500
hodorow *et al.*[26] ..	220	21 × 9·0	60	630	1·0
eck and Caswell[10]	14	0·9	—	6·0	—
ost and Shiren[134] ..	14	20	120	40	—

(3.2) Miscellaneous Techniques

t has been proposed by Flesher and Cohn[40] and R-Shersby-rvie[57, 58] that sleeves of solid dielectric material be employed give a slow-wave structure. Such waveguides were found be lossy, but better success was obtained with the aniso-pic dielectric of R-Shersby-Harvie *et al.*[59]; the material, order to be satisfactory, must possess a higher dielectric nstant in the radial than in the axial direction. Naturally curring materials were not sufficiently anisotropic, and thus artificial dielectric medium, consisting of a number of nly spaced thin ceramic discs, was employed. The material the discs was titanium dioxide, with a dielectric constant about 95, and they were accurately ground after firing. ch dielectric loading enables accelerators of smaller physical meter to be used, while the r.f. power required is about one-f that in an equivalent all-metal corrugated guide. The main rameters which affected the shunt impedance were the dielectric constant and the Q-factor, the degree of lamination $(D - d)/D$ and radius a of the central hole. Figs. 8(*a*) and 8(*b*) show the effect upon copper and dielectric losses of varying $(D - d)/D$ for $a = 1$ cm and $\lambda = 10$ cm, the outer radius not varying much from 3 cm. Figs. 8(*c*) and 8(*d*) show respectively the series conductance and variation of the group velocity.

The figure of merit of a linear accelerator can be improved by closing the ends of the slow-wave structure to make it resonant, all the input power being dissipated in the walls. With usual values of Q-factor the time required for oscillations to build up to, say, 90% of their final value is of the order of 1 microsec. Such a standing-wave accelerator possesses discrete modes of oscillation, and to achieve adequate separation from neighbouring modes, Lawton and Hahn[95] operated their accelerator near the middle of the pass-band. Other resonant accelerators have been constructed by Sarazin[140] and Demos, Kip and Slater,[36] who obtained 18 MeV in a length of 21 ft: the accelerator was fed by 21 tunable magnetrons, the resonant structure having the advantage that it can stabilize the frequency of these self-oscillators.

High energy from short accelerators may be achieved by partial resonance using feedback from the output to the input. For the method described by Saxon,[141] the basic circuit is shown in Fig. 9(*a*) from which it will be seen that the residual r.f. power from the accelerator was fed back, suitably phased, into a waveguide bridge where it combined with the input power and recirculated. The bridge was so designed that if two conjugate arms were fed with powers kP and P respectively, then, if the phasing was correct, one of the other arms had a power flow of $(k + 1)P$ and the remaining arm zero. The number k is unity for the hybrid-T, hybrid ring and 3 dB coupler, but may have any value for the circular hybrid junction.

If P_a, P_l and P_s are the power flows of the accelerator, resistive load and source respectively, Fig. 9(*b*) gives the power ratios P_a/P_s and P_l/P_s for the case $k = 1$ as a function of loop attenuation. It may be seen that when the latter is 3 dB the power build-up ratio is 2, and no power enters the resistive load. For any other particular value of attenuation, if a bridge of correct ratio k is used, the maximum build-up power ratio will be as given by the dotted line. It will be seen that a unity ratio junction may be used over a wide range of attenuation without serious loss of power build-up. Such a feedback circuit was employed by Miller[109, 110, 111] in an accelerator of 9 ft length to give 8 MeV at a beam current of 60 mA for an input power of 1·86 MW. Other machines have given 4 MeV with a beam current of 200 mA and a peak r.f. power of 2·0 MW.

Linear accelerators may be employed for the production of high-energy light-ion particles,[11, 12] but the design presents new problems and difficulties on account of the much lower phase velocities involved. An iris-loaded waveguide would lead to prohibitive r.f. losses due to attenuation unless the output energy exceeded, say, 100 MeV. Protons of modest energy have been achieved by Septier[148, 149] and Chick and Petrie[23, 25] using a helix as a slow-wave structure. The wire helix was wound on a glass tube which was evacuated to allow the proton beam to pass along the axis while a pressure of 150 lb/in^2 was maintained outside the tube to prevent r.f. breakdown between turns. The helix radius was 1 cm, and the pitch varied from 4 mm at the input to 4·6 mm at the output end to accelerate particles from 2·5 to 4 MeV. This acceleration was obtained in a 4 ft length

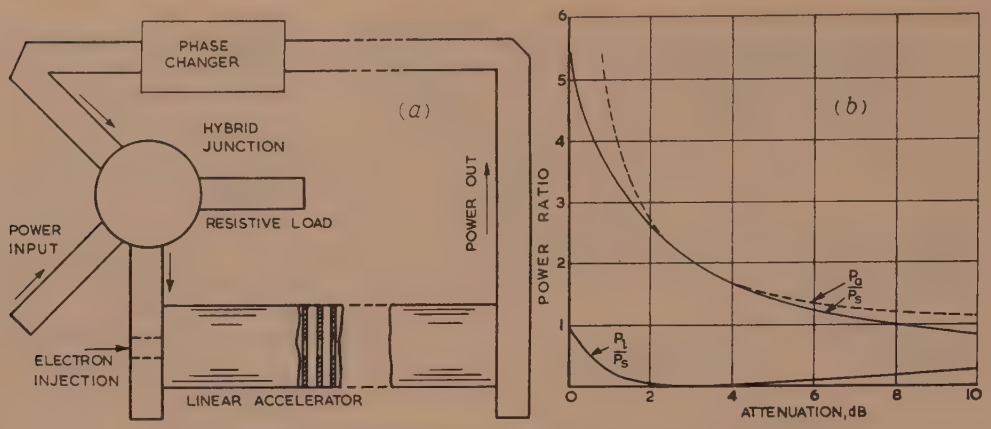


Fig. 9.—Feedback with a travelling-wave accelerator.
(*a*) Basic waveguide circuit.
(*b*) Build-up power ratio.
—— $k = 1$.
---- k = Optimum.

for a peak power flux of 500 kW at 300 Mc/s, the beam current during the 6 microsec pulses being 25 μA. The helix is a wide-band structure, and Gallop[46] has proposed its use for the production of protons having a narrow spectrum but with a mean energy variable over a wide range, say 3–50 MeV, by adjustment of the exciting frequency.

(4) CONSTANT-FIELD ORBITAL ACCELERATORS

(4.1) Cyclotrons

The first orbital electronuclear accelerator to be successfully constructed and operated was the fixed-frequency cyclotron described by Lawrence and Livingston.[93, 94] The general arrangement of a typical cyclotron is shown in Fig. 10(*a*) and is seen to consist of two D-shaped electrodes between which an r.f. electric field is applied, while there is also a magnetic field transverse to the electrodes. The particles are usually heavy ions and move at sufficiently low velocities so that $W_k \ll W_0$ and the frequency of rotation given by eqn. (19) becomes

$$f = eHc^2/2\pi W_0 = eH/2\pi m \quad . \quad . \quad . \quad . \quad (26)$$

being thus practically constant. The radio frequency is adjusted to be in synchronism with this particle motion.

If the fringing of the electric field between the dee edges is small, the particle picks up[29] an energy of $eV_g \cos 2\pi ft$ at each transit of the gaps, where $2\pi ft$ represents the phase of the electric field at which the particle starts. After N complete revolutions the particle has a total energy given very nearly by

$$W = 2eNV_g \cos 2\pi ft \quad . \quad . \quad . \quad . \quad . \quad (27)$$

The particles are injected by means of a suitable gun, and when they have reached the desired energy the beam is taken through a thin foil window by means of a deflector system. The frequency employed is about 20 Mc/s with power inputs of about 300 kW, the Q-factor of the electrode circuit being usually several thousand. A useful upper limit for proton acceleration is about 50 MeV with a magnet pole of 40 in diameter, but since a pulse of particles is produced for each cycle of the accelerating voltage the intensities of the beam may be up to 300 μA mean. Three-phase cyclotrons have been constructed[73, 139, 154] for the acceleration of protons, deuterons and tritons.

A typical magnetic field in a cyclotron is 12 000 oersteds, which would require a magnet of 400 tons and a dissipation of 60 kW. The maintenance of magnetic field over the whole area included inside the final orbit leads to a rapid increase of cost with output energy. Moreover, the maximum energy obtainable from the normal cyclotron is limited by the radial decrease of magnetic field required for orbital stability and the relativistic increase in mass of the accelerated particles. Eqn. (19) shows that f, and thus r, decreases as the energy W_k increases, and thus the particle fall out of phase with the accelerating field.

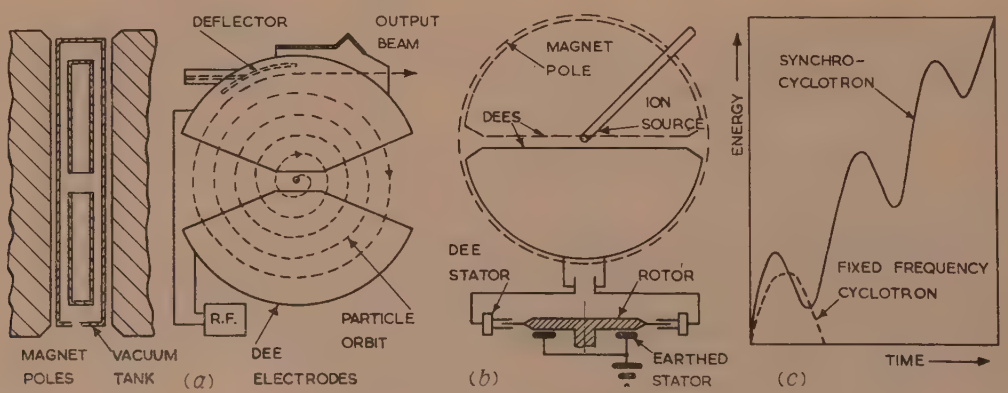


Fig. 10.—Types of cyclotron.
(*a*) Fixed-frequency cyclotron.
(*b*) Variable-frequency or synchro-cyclotron.
(*c*) Energy against time for both machines.

(4.2) Synchro-cyclotrons

Methods for overcoming the relativistic limitation of the cyclotron were proposed independently by Oliphant,[122] Veksler[168] and McMillan.[100] They showed that the acceleration of very-high-energy particles could be carried out successfully by progressively reducing the frequency of the r.f. electric field. Such a frequency-modulated or synchro-cyclotron is illustrated in Fig. 10(*b*), the r.f. energy being applied to one dee electrode only and the other being earthed.

Consider a particle starting from the centre at the instant when the frequency of the r.f. field is $eH/2\pi m_0$. If this frequency remains constant, the particles will gradually fall behind in phase until, after a given radius, they will begin to be decelerated and finally return to the centre as shown by the dotted line of Fig. 10(*c*). If, however, the radio frequency is decreased slowly, the particles will not fall behind in phase so quickly and will reach a larger radius before deceleration. An important additional feature is that during deceleration they catch up in phase again quite rapidly and so are again accelerated. This process continues until the particles reach the maximum radius available, the variation of energy with time being shown in Fig. 10(*c*). The particle motion follows an orbit whose radius oscillates steadily about a continuously expanding spiral; the larger the r.f. voltage and the slower the change in frequency the more violent are the oscillations.

Confirmation of this phase-stability principle was made by Richardson *et al.*[138] by modifying a 37 in diameter cyclotron. Since then a number of large synchro-cyclotrons have been constructed for the acceleration of protons, and typical details are given in Table 5, the frequencies employed being about 20 Mc/s with a repetition speed of 200 c/s. For an energy of 400 MeV the magnet weight is 1 650 tons with a dissipation of 840 kW. Since the magnetic field over the final orbit in an iron-cored magnet cannot much exceed 15 000 oersteds, the diameter of a magnet for a 1 GeV accelerator would be at least 25 ft; because the orbits cover the whole region within this diameter the magnet sets an economic limit to the output energy.

Table 5

SYNCHRO-CYCLOTRONS FOR PROTON ACCELERATION

Description by	Final orbit diameter	Output	
		Energy	Mean current
	in	MeV	μA
Livingston[98]	184	200	—
Barnes *et al.*[8]	130	240	0·1
Pickavance *et al.*[132] ..	—	180	0·5
Chick and Miller[24] ..	—	400	1·0
C.E.R.N.[176]	—	600	—

(4.3) Electron Cyclotrons

The electron cyclotron, or microtron, is an accelerator in which all the particle orbits are cotangential at a point in the acceleration gap of a resonant cavity as shown in Figs. 11(*a*) and 11(*b*). This machine was first suggested by Veksler[168] and constructed in practical form by Henderson *et al.*[63] and Redhead *et al.*[137] The electrons slip one cycle of phase on each orbit through the constant magnetic field and acquire a constant energy increment ΔW on each transit of the resonator gap. It may be shown[79] that successive orbits then differ in radius by $v\Delta W/Hec$ and hence in time traversal by $2\pi/v$ times this quantity. This difference is one r.f. cycle if

$$H = 2\pi f \Delta W/ec \quad . \quad . \quad . \quad . \quad . \quad (28)$$

In the simplest case ΔW is made equal to W_0.

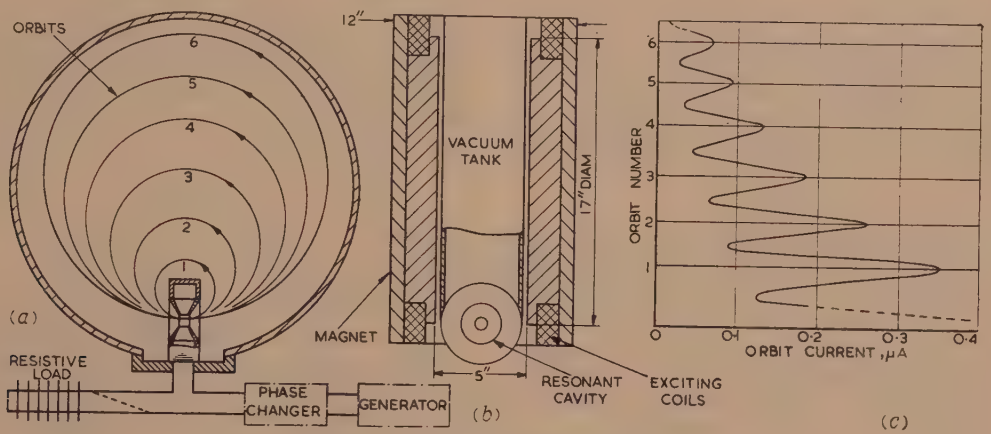


Fig. 11.—Electron cyclotron or microtron.
(*a*) Electrical circuit and the orbits.
(*b*) Magnet assembly.
(*c*) Currents in the various orbits.
The machine operates at 3 Gc/s.

The problem of injection is usually overcome by accelerating electrons from rest, using field emission from the resonator lips as the source. It is relatively easy to extract the particle beam from the system because of the large separation of the orbits. The electrons in the microtron possess phase stability if they cross the resonator gap after the electric field has reached its maximum. This stability makes it possible to introduce a small tapering of the magnetic field, which produces focusing with respect to the median plane. The increase of mass of the electron due to acceleration also causes its transverse components of velocity to decrease, since the transverse momentum is constant. More-detailed study of the range of phase angles for stable acceleration has been made by others.[62, 71, 144] To ensure efficient operation the resonant cavity should, in general, possess as high a shunt resistance and associated Q-factor as is permitted[80] by the restrictions imposed by the geometry of the apparatus as related to the orbital conditions.

The design and operation of a 4·5 MeV microtron has been described by Henderson, Heyman and Jennings.[61] The machine operated at a frequency of 3 Gc/s and at a magnetic field of about 1 000 gauss. The diameter of the final orbit was approxi-

mately 30 cm, and the power input was 500 kW with a pulse duration of 2 microsec at a repetition frequency of 200 c/s. A resistive load was coupled in series with the cavities, and a phase-changer was adjusted so that the generator was effectively an integral number of half-wavelengths from the resonator in order to ensure optimum frequency stability. A plot of typical orbit currents, observed by means of a movable probe, is shown in Fig. 11(*c*). A 3 MeV microtron operating at a frequency of 9·5 Gc/s has been constructed by Kaiser and Mayes.[81] With 100 kW input it was possible to obtain operating modes with 102, 127, 170 and 255 keV energy gain per transit. The design and scaling of microtrons, together with experimental results, has been given by Kaiser;[78] a design for a frequency of 24 Gc/s was included.

(5) INDUCTION-TYPE ORBITAL ACCELERATORS

(5.1) Betatrons

A further class of orbital accelerators is the induction type, in which the magnetic field varies. One example is the betatron developed by Kerst[86, 89] and illustrated in Fig. 12(*a*). The changing magnetic flux induces a tangential electric field which continuously accelerates the electrons. The rate of rise of the magnetic field is adjusted to keep in step with the momentum of the accelerated particles so that they are constrained to move in an annular space termed the doughnut.

In examining the theory of the betatron, Steenbeck[158] and Kerst and Serber[87] showed that the kinetic energy acquired by the particles in one turn is given by

$$\Delta W_k = ed\Phi/dt = 2\pi rF = 2\pi r dp/dt \quad . \quad . \quad (29)$$

where $d\Phi/dt$ is the rate of change of flux inside the orbit. Integration of eqn. (29) gives

$$p - p_0 = e(\Phi - \Phi_0)/2\pi r \quad . \quad . \quad . \quad . \quad (30)$$

so that the change of momentum is proportional to that of flux. For a particle starting from rest, so that $p_0 = 0$,

$$p = e\Delta\Phi/2\pi r \quad . \quad . \quad . \quad . \quad . \quad (31)$$

where $\Delta\Phi$ is the total change of flux. In order that the particles remain in the orbit, eqns. (14) and (15) give

$$Hr = p/e = \Delta\Phi/2\pi r \quad . \quad . \quad . \quad . \quad (32$$

Hence there exists an equilibrium orbit of constant radius r_0 provided the magnetic field is made to increase with the flux in such a manner that the relationship

$$\Delta\Phi = 2\pi r_0^2 H \quad . \quad . \quad . \quad . \quad . \quad (33$$

is continuously satisfied, i.e. the flux inside the orbit must be made to grow at a rate twice that corresponding to the rising of a uniform field H over the area inside the orbit. If the particles are injected with a finite energy appropriate to the field at that instant, it is necessary thereafter only to satisfy the relationship

$$\Delta\Phi = 2\pi r_0^2(H - H') \quad . \quad . \quad . \quad . \quad (34$$

where H' is the required orbital field at injection.

Decrease of the magnetic field with radius at the orbit provides magnetic focusing with respect to the median plane, and, if the field falls off less rapidly than $1/r$, the orbits are stable; an electron deflected from its circular path will undergo an oscilla

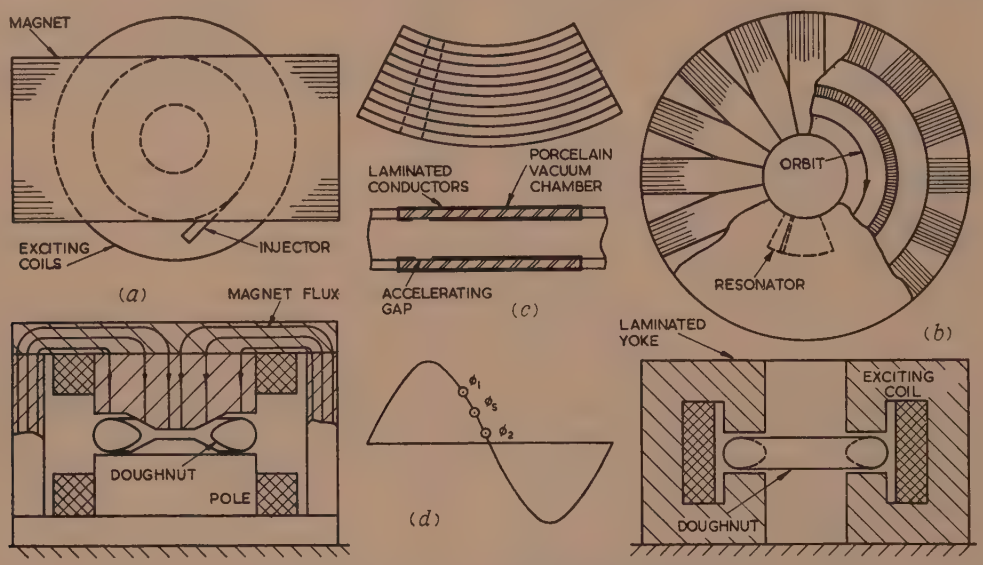


Fig. 12.—Induction cyclic accelerators for electrons.
(*a*) Betatron. (*c*) Accelerating cavity.
(*b*) Synchrotron. (*d*) Phase diagram.

In examining the theory of the betatron, Steenbeck[158] and Kerst and Serber[87] showed that the kinetic energy acquired by the particles in one turn is given by

$$\Delta W_k = ed\Phi/dt = 2\pi rF = 2\pi r dp/dt \quad . \quad . \quad (29)$$

where $d\Phi/dt$ is the rate of change of flux inside the orbit. Integration of eqn. (29) gives

$$p - p_0 = e(\Phi - \Phi_0)/2\pi r \quad . \quad . \quad . \quad . \quad (30)$$

so that the change of momentum is proportional to that of flux. For a particle starting from rest, so that $p_0 = 0$,

$$p = e\Delta\Phi/2\pi r \quad . \quad . \quad . \quad . \quad . \quad (31)$$

where $\Delta\Phi$ is the total change of flux. In order that the particles

tion about that path, the oscillation amplitude decreasing with increasing particle energy. The magnetic field is made to oscillate at the mains frequency by making the magnet induc tance resonate with a bank of capacitors, the maximum flu density at the orbit being about 5000 gauss.

A betatron capable of providing energies as high as 100 MeV has been developed by Westendorp and Charlton.[171] This machine had a pole face of 76 in diameter and weighed 130 tons and the magnet absorbed 200 kW on full load. The electron were injected with a voltage of about 50 keV and circled th magnetic flux about 250 000 times, acquiring on each revolutio an average additional energy of about 400 eV. A 24 MV capacitor bank was provided. Other machines which have bee constructed include examples for 15 MeV,[143] 20 MeV[24, 103] an 315 MeV.[88] Hentze[64] has described iron-free betatrons wit operating frequencies in the range 2·5–8·0 kc/s. The betatro is of no economic use in accelerating protons, since, for the sam energy as electrons, a magnet of 40 times the radius would b required.

(5.2) Electron Synchrotrons

A reduction in the magnet size of the betatron can be achieved y accelerating the electrons by an r.f. electric field, as is carried ut for ions in the cyclotron. The radio frequency must be ocked to the average electron frequency, and, provided the nergy is 2 MeV or more, the electron velocity, and thus the requency, remains sensibly constant. Such a machine, termed ne synchrotron, was proposed independently by Veksler[168] and McMillan.[100]

The arrangement is shown in Fig. 12(*b*). The orbit radius oes not change much, and thus a ring-shaped magnetic field uffices, while the particles are again confined to a doughnut. he short-circuiting of the varying magnetic field by the r.f. ystem can be avoided by taking advantage of the difference in kin depth for the radio and magnetic-field frequencies. To onserve space the resonator must have small vertical dimensions, nd one design described by Fremlin and Gooden[41] used a pecial high-frequency porcelain. The resonator was formed rom a section of the vacuum chamber as shown in Fig. 12(*c*), gap being left on the inner surface to provide the accelerating ield. In this example the metal forming the resonator walls vas laminated to reduce eddy currents. The r.f. powers required n synchrotrons are from 1 to 10 kW, and the r.f. voltages from a few hundred to 10000 volts or more, with frequencies from 10 to 500 Mc/s.

The electrons require, on the average, a definite amount of energy to be given to them per revolution in order that they may remain inside the doughnut. The electrons are stable[82, 83] with respect to the phase at which they arrive at the acceleration gap, as may be seen from Fig. 12(*d*). The stable phase ϕ_s is such hat the particles receive just the correct energy. If the particles arrive earlier, say at ϕ_1, they receive more than the required energy and follow a circle of larger radius which delays them at he next transit. A similar process occurs for particles arriving ate, as at ϕ_2. These phase oscillations are damped at a rate proportional to $W^{-1/4}$, and thus the r.f. voltage is always made arger than the minimum energy to be added per revolution. Many synchrotrons commence their period of acceleration operating as betatrons, and when the rate of rise of magnetic ield falls off owing, say, to saturation of the core, the increments of energy imparted by the r.f. field ensure smooth and stable change to synchrotron operation.

An early demonstration of the synchrotron principle was made by Goward and Barnes,[52] who modified an existing 4 MeV betatron to give 8 MeV. Elder *et al.*[37] have described a 70 MeV synchrotron, while Chick and Miller[24] mention one for 340 MeV, he magnet weighing 88 tons with a dissipation of 60 kW, the repetition speed being 4·5 c/s and the mean beam current $2{\cdot}5 \times 10^{-4}\mu$A. An iron-free synchrotron was suggested by Post[133] and put into practice by Jones *et al.*[76] to give 300 MeV, the magnetic fields being produced directly by large currents flowing in coils suitably disposed near the electron orbit.

One upper limit for the energy attainable in an orbital accelerator is set by the radiation of energy from the particles due to the centripetal acceleration required to maintain the circular orbit. This radiation loss increases with energy, and a balance is reached when it is just replaced by the energy acquired from the applied fields. Analysis of this radiation shows[72, 101, 142] that the loss of energy per revolution is, to a first-order approximation, given in electron volts by

$$\Delta W = 6 \times 10^{-7}(W/W_0)^4/r \quad . \quad . \quad . \quad . \quad (35)$$

Even for moderate energies of around 100 MeV this radiation[105, 106, 136] is partly in the visible spectrum.[147] With electrons, and for energies of 10^9 volts and r of 300 cm, the loss of energy per revolution due to radiation is about 30 keV. Since this loss increases with the fourth power of the particle energy, it becomes excessive for energies greater than, say, 3 GeV.

(5.3) Proton Synchrotrons

It will be seen from eqn. (35) that radiation loss is inversely proportional to the fourth power of W_0, and thus much higher energies are achievable from orbital accelerators by employing light ions such as protons. A machine for the acceleration of protons was suggested by Wideroe,[173] while the proton synchrotron was proposed by Oliphant, Gooden and Hide[121] and Brobeck;[20] theoretical studies by Gooden, Jensen and Symonds[51] and Twiss and Frank[162] showed that such a device is practicable. This machine is similar to its electron counterpart in that a ring-shaped magnet guides the particles in a circular path, and, at one or more locations on this orbit, an r.f. accelerating field, synchronized with the particle motion, provides increments of energy.

The operating conditions are that W_k is initially small compared with m_0c^2 but finally exceeds it many times, so that v/c gradually increases from a very small value to near unity. The frequency and magnetic field must hence follow a suitable variation with time to achieve acceleration and constancy of orbit radius. The final energy of the particle is determined by the maximum magnetic field H in a relation which, from eqns. (13) and (19), is

$$r = (W^2 - W_0^2)^{1/2}/Hec \quad . \quad . \quad . \quad . \quad (36)$$

Proton synchrotrons usually have a magnetic field which rises to its maximum value of about 15000 oersteds in about one

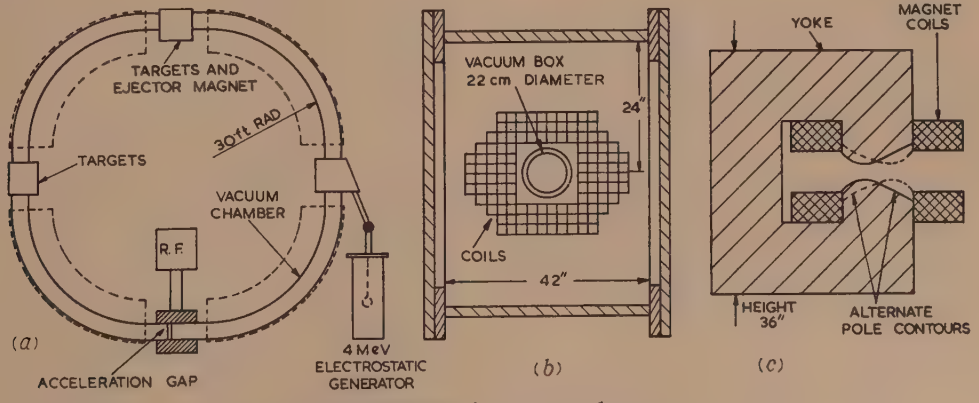


Fig. 13.—Types of proton synchrotron.

(*a*) Plan view of the 3 GeV cosmotron.
(*b*) Magnet cross-section for an air-cored 10 GeV machine.
(*c*) Magnet cross-section for a 25 GeV alternating-gradient machine.

second, which means that the magnet yoke may have quite thick laminations. In the cosmotron described by Blewett,[14] and outlined in Fig. 13(*a*), the orbit radius of 30 ft gave a final energy of 3 GeV. The radio frequency varied from 370 kc/s to 4 Mc/s, the injected beam having a pulse length of 100 microsec with a cycle time of 5 sec. The beam current during the pulse was about 1 μA, so that the mean current was quite small. The magnet required 336 000 ampere-turns, the power supply being 7 000 amp at about 4 000 volts under full load. The 21 MVA 12-phase generator, coupled to a 45-ton flywheel, was connected to the magnet through 24 ignitrons that acted as rectifiers during the acceleration cycle. At the end of the 1 sec acceleration period, the ignitrons became inverters to return the magnet's stored energy to the flywheel.

In an attempt to achieve high energies without the very large expenditure necessary for usual machines, a 10 GeV proton synchrotron of a completely unconventional design is being designed and constructed by Oliphant.[123] The radius of the proton orbit is reduced to 12 ft by increasing the peak magnetic field to 100 000 gauss, and the radio frequency is varied during acceleration over a range of 1 : 8. The magnet consists of an array of conductors suitably arranged, as shown in Fig. 13(*b*), to give the correct field distributions. The conductors are water-cooled and at peak field the current is $5{\cdot}9 \times 10^6$ amp with a current density of 5 000 amp/cm^2. The rectangular conductors are held together against the bursting force of 45 tons/in length by surrounding them with a laminated structure of Duralumin plates. The power source is a homopolar generator, contact with the four steel discs, 139 in diameter, 10½ in thick, rotating at 900 r.p.m., being made by jets of liquid sodium. The energy dissipated is replaced by a rectifier supply, so that the pulses of current can be repeated only at intervals of about 10 min. There are 10^8–10^9 particles in a pulse.

(6) ALTERNATING-GRADIENT FOCUSING

Radial and axial stability in both electron and proton synchrotrons is achieved, as in the betatron, by radial tapering of the magnetic field. The strength of the restoring forces is limited by the stability condition, $0 < n < 1$, where

$$n = -(r/H)(dH/dr) \quad . \quad . \quad . \quad . \quad . \quad (37)$$

The restoring forces lead to stable 'betatron' oscillations, the amplitudes being due to deviations from the equilibrium orbit caused by angular and energy spread in the injected beam, scattering by residual gas, magnetic inhomogeneities and frequency errors. The frequencies of the axial and radial oscillations are given in terms of the frequency of revolution by

$$f_z = n^{1/2} f \text{ and } f_r = (1 - n)^{1/2} f \quad . \quad . \quad . \quad (38)$$

The corresponding amplitudes are inversely proportional to these oscillation frequencies for a given angular deviation. Therefore, the aperture required to accommodate either mode can only be reduced at the expense of the other mode, and the minimum aperture for both occurs with $n = 0{\cdot}5$.

It was shown by Courant, Livingston and Snyder[33] that the focusing forces can be considerably increased by letting n vary in azimuth. If the circular orbit consists of N sectors of equal length, the best results are obtained when N is large and the sectors have equal and opposite gradients. The centre of the region of stability occurs when

$$|n| = N^2/16 \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

and the effective frequency of the 'betatron' oscillations is given by

$$f_z = f_r = \mu N/2f \quad . \quad . \quad . \quad . \quad . \quad (40)$$

where μ is a trigonometrical function of n and N. For example if $N = 240$ and $n = 3\,600$, the radial and axial aperture requirements are respectively about 1/24 and 1/20 that for the corresponding synchrotron with a constant $n = 0{\cdot}6$. This arrangement, in which the magnetic-field gradient has successively high positive and high negative values, is known as 'strong' or alternating-gradient focusing.

Although Blewett[15] has proposed the use of 'strong' focusing in linear accelerators, most attention has been given[49, 50, 90, 91, 104] to proton synchrotrons in which the smaller beam aperture leads to a considerable saving in magnet size and weight. Accelerators employing this technique are being constructed[13] for energies up to 25 GeV. The cross-section through the magnet of a typical design is shown in Fig. 13(*c*), the dotted line representing the pole contour for the next magnet sector in which the magnetic field gradient is reversed. The total magnet weight is about 300 tons, injection is by means of a 50 MeV linear accelerator and the circumference of the machine is about 600 metres. Designs for even higher-energy machines up to 0·1 TeV have been given by Mints *et al.*[113, 114, 115]

Alternating-gradient focusing has been shown by Symon *et al.*[157] to have advantages in fixed-field machines, and the principle has been confirmed in practice by Coles *et al.*[30] and Jones *et al.*[75] The radial-sector design achieves 'strong' focusing by having the fields in successive focusing and defocusing magnets vary in the same way with radius but with alternating signs. Since the orbit in the reverse-field magnet bends away from the centre, the machine is, however, much larger than a conventional alternating-gradient synchrotron. This disadvantage is overcome in the spiral-ridge type, in which the magnetic field consists of a radially-increasing azimuthally-independent field on which is superimposed a radially-increasing azimuthally-periodic field. The ridges (maxima) and troughs (minima) of the periodic field spiral outward at a small angle to the orbit. The particle, crossing the field ridges at a small angle, experiences alternating gradient focusing. Since the magnetic field is constant, the beam pulse rate is determined only by the repetition rate of the r.f. modulation cycle, and thus the intensity is high. This principle can be applied to synchrotrons,[174] betatrons and cyclotrons.[116, 117]

As accelerators of higher and higher energy are built, their usefulness is limited by the fact that the energy available for creating new particles is that measured in the centre-of-mass system of the target and bombarding particles. In the relativistic limit, this energy rises only as the square root of the accelerator energy. However, if two particles of equal energy travelling in opposite directions could be made to collide, the available energy would be twice the whole energy of one particle. For example, a collision of two 25 GeV protons produces an energy in the centre of mass equivalent to that produced by a 1·3 TeV machine with the target at rest. High beam densities are needed for sufficient interactions to take place, and this requires successive pulses of particles to be 'stacked' at high energy.

The high intensity of fixed-field alternating-gradient machines has made practicable this principle of colliding beams. Such an accelerator would, for example, consist of two orbital machines tangential to one another, so that the orbits of the two beams have a common segment at the high-energy radii. In this method the high-energy orbits suffer perturbations because of the field of the other machine, so that very accurate adjustment is required to avoid betatron oscillation instability. This difficulty is avoided by O'Neill,[124] who proposes the use of two storage rings in conjunction with a single accelerator. The full-energy beam of the accelerator is brought out at the peak of each cycle, focused and bent so that beams from alternate magnet cycles enter each ring in turn. The rings are tangential, so that collision of the

vo stored beams takes place, but rather elaborate techniques re required to manipulate particles in the necessary extraction nd injection processes. Ohkawa[120] discusses a colliding-beam ystem in which both beams are circulating in opposite directions i a single accelerator. The machine is essentially a modified idial-sector fixed-field alternating-gradient accelerator in which ie magnetic fields are produced by equal numbers of positive nd negative field magnets of equal strength. Particles can be ccelerated in both directions by an r.f. voltage in a cavity and tacked' at any desired energy.

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DISCUSSION ON 'SPACE CHARGE AS A SOURCE OF FLICKER EFFECT'* AND 'THE CAPACITANCE BETWEEN DIODE ELECTRODES IN THE PRESENCE OF SPACE CHARGES'†

Mr. W. F. Lovering (*communicated*): The author takes as his starting-point in Paper No. 2493* an equation derived in an earlier paper, No. 2333.† Unfortunately, in the earlier paper he has made an error in logic. Eqn. (7) of that paper is derived from the argument of Section 3, par. 4, which assumes that the rate of escape of electrons from the cathode is independent of anode voltage. This assumption is not correct for a space-charge-limited diode, so that the calculation in Section 4 is invalid.

In addition, however, the author's treatment of eqn. (11) is mathematically incorrect. Since the quantities

$$\left(\frac{\partial V}{\partial x}\right)_A \text{ and } \left(\frac{\partial V}{\partial x}\right)_C$$

are functions of V it is not permissible to substitute approximate values for them and differentiate the resultant expression for Q_s.

It follows that none of the conclusions drawn in the papers may be considered valid.

Dr. C. S. Bull (*in reply*):

Paper No. 2493.*—This paper depends on eqn. (1) only in the sense that the electronic capacitance should be in general of appreciable positive or negative magnitude. That this is in fact the case has been established for many years by theoretical and experimental studies by many authorities. After the first two paragraphs of Section 1 the paper proceeds without further reference to the value of C_e. All the conclusions drawn about fluctuations are entirely independent of the fact that I propose one particular picture of the action of a valve in preference to those of earlier authors.

Paper No. 2333.†—In the third paragraph from the end of Section 1, I refer explicitly to the dependence of anode current on anode voltage. Since this does not depend on dV/dt, no capacitive current is developed by it. The calculation made in Section 4 is therefore valid, and is correctly based on earlier parts of the paper.

Mr. Lovering points out the error in treating eqn. (11). Closer consideration of this point is tedious but leads to the conclusion that the capacitance just above the saturation point is infinite. Fig. 2 should therefore have, in place of the jump of $2C$ as the anode voltage passes upwards through V_s, a jump of infinity. In all other respects the curves indicate correctly the course of capacitance versus voltage.

The appearance of this infinite peak depends on the assumption of zero emission velocities. It would obviously not be expected in actual valves. Fig. 2 is therefore a good indication of the expected behaviour in spite of the error of differentiation.

Mr. Lovering's remark that none of my conclusions is valid is thus untenable.

* BULL, C. S.: Paper No. 2493 R, March, 1958 (see 105 B, p. 190).
† BULL, C. S.: Paper No. 2333 R, July, 1957 (see 104 B, p. 374).

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AN INVESTIGATION OF HIGH-FREQUENCY DIRECTION-FINDING ERRORS CAUSED BY NEARBY VERTICAL RERADIATORS

By C. W. McLEISH, M.Sc., and R. S. ROGER, B.App.Sc.

(*The paper was first received* 11*th April, and in revised form* 14*th August*, 1958.)

SUMMARY

The theory of reradiation from resonant conductors is reviewed, and the susceptibilities to error of three types of direction-finding aerial are compared. Measured errors due to reradiation confirm theoretical values derived from a simple expression in cases of thin linear conductors in simple resonant modes.

LIST OF SYMBOLS

R = Ratio between reradiated and direct field strengths.
l = Length of earthed reradiator.
x = Distance of reradiator from receiver.
d_1, d_2 = Distance of extremities of reradiator and its image respectively from receiver.
γ = Ground-wave propagation coefficient.
σ = Conductivity of earth.
ϵ = Relative permittivity of earth.
ϕ = Bearing error.
β = Time phase between reradiated and direct fields.
θ = Horizontal angle between reradiated and direct fields.
Φ = Bearing error when fields are cophasal.
f_i = Cyclic interval of bearing-error changes with frequency.

(1) INTRODUCTION

Reradiation from metallic structures near the aerial is one of the sources of error in radio direction-finding. Therefore, in an evaluation of an aerial site, it is useful to be able to estimate the errors to be expected from simple reradiating structures. Several papers[1–3] describe the fundamental problems of siting, and it is the purpose of this paper to present in a simple form the expression for the maximum error caused by vertical reradiators near a vertically polarized aerial. Similar considerations could, of course, apply in the case of horizontal polarization.

If the reradiator is assumed to be in the horizontal plane through the aerial, the maximum error will occur near the frequency of primary resonance. Struszynski[4] has described methods of measuring the resonant frequencies of structures. It has been shown[5] that for a thin earthed vertical element on a perfectly conducting plane, the ratio between the reradiated and incident field strengths is given approximately by

$$R = 1{\cdot}04\frac{l}{x}\cos\frac{\pi}{2}\left(\frac{d_2 - d_1}{2l}\right) \quad . \quad . \quad . \quad . \quad (1)$$

where the geometry is defined in Fig. 1. When a factor γ is applied to allow for attenuation of the surface wave over an imperfectly conducting ground, and the receiving point is relatively close to the ground, eqn. (1) reduces to

$$R = \frac{1{\cdot}04\gamma l}{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This holds also for unearthed vertical reradiators, where l is half the length. Fig. 2 gives curves for γ derived from Norton[6] for sea water, good soil and poor soil.

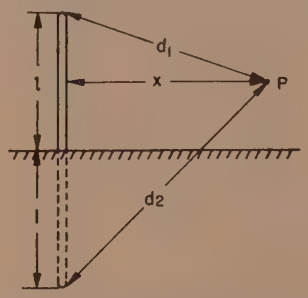


Fig. 1.—Dimensions for earthed reradiator considered.

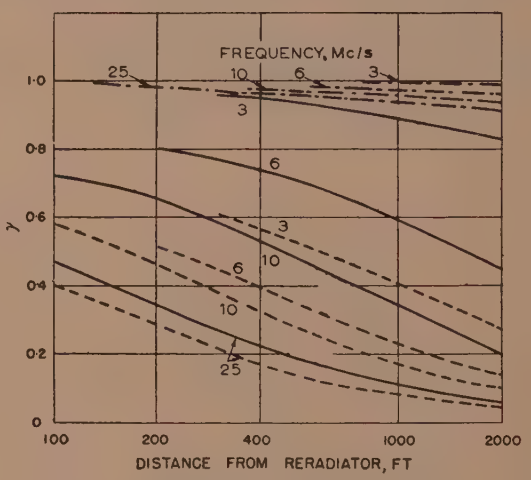


Fig. 2.—Ground-wave propagation coefficient.
—·— Sea water: $\sigma = 4 \times 10^{-11}$ e.m.u., $\epsilon = 81$.
—— Good soil: $\sigma = 1 \times 10^{-13}$ e.m.u., $\epsilon = 10$.
---- Poor soil: $\sigma = 1 \times 10^{-14}$ e.m.u., $\epsilon = 10$.

The error introduced by reradiation may be expressed approxi mately in terms of the amplitude ratio, R, the horizontal angle θ, and the time phase, β, between the reradiated and the direc fields as

$$\phi \simeq R\cos\beta f(\theta) \quad . \quad . \quad . \quad . \quad . \quad (3$$

for small values of R. The function of θ is determined by th antenna polar pattern, and may be called the susceptibility o the antenna to reradiation. Fig. 3 shows this function for th single-loop, Adcock and spaced-loop aerials, the derivation o which is outlined in Section 5. The maximum error for a give configuration is obtained when the time phase is adjusted t give $\cos\beta = \pm 1$, so that

$$\Phi \simeq Rf(\theta) \quad . \quad . \quad . \quad . \quad . \quad . \quad (4$$

An analysis of a number of types of direction-finding aerial by Hopkins and Horner[7] provides the r.m.s. value of $f(\theta)$ fo each type. This figure is particularly useful in the statistica evaluation of the susceptibility of direction-finders to randor site errors.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. McLeish and Mr. Rogers are in the Defence II Section of the National Research Council of Canada.

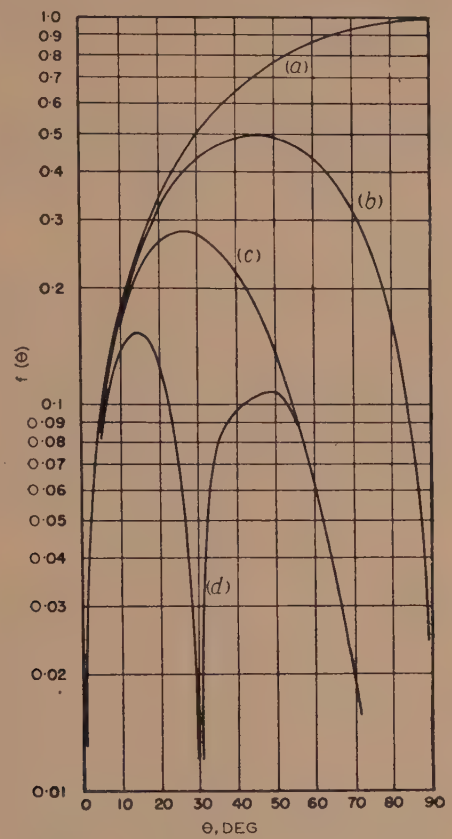


Fig. 3.—Values of $f(\theta)$ for various aerials.
(*a*) Loop and Adcock: $d < 0{\cdot}1\lambda$.
(*b*) Coaxial spaced loops: $d < 0{\cdot}1\lambda$.
(*c*) Coaxial spaced loops: $d = \lambda$.
(*d*) Coaxial spaced loops: $d = 2\lambda$.

For a particular aerial it may be convenient to express the maximum error that a certain resonant reradiator can produce in terms of

$$\Phi_{max}x = 1{\cdot}04\gamma l f(\theta)_{max}\left(\frac{180}{\pi}\right) \text{ degree-metres} \quad . \quad (5)$$

Although the right-hand side is not independent of distance, the value of γ may be applied as a correction in particular cases.

(2) MEASUREMENTS

A portable coaxial spaced-loop direction-finder[8] was used to measure the effect of some typical reradiators. Below 20 Mc/s, readings of radio bearings could be repeated to within about

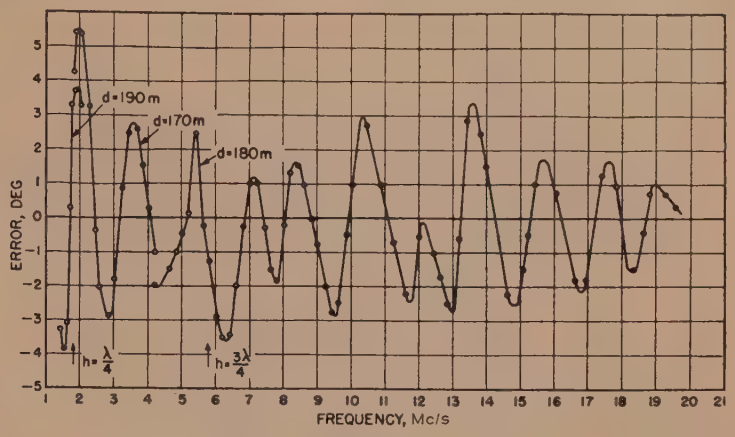


Fig. 4.—Variation of error with frequency for water tower.

5′ under normal conditions. $f(\theta)$ is maximum at 45° from the plane of the loops, so all meaurements were made with this angle between the direct and the reradiated fields. The transmitter was placed equidistant from the reradiator and the direction-finder, to establish equal field intensities. In order to vary β, the transmitted frequency was varied in small increments, and an observation of the error in bearing was made at each frequency. The resulting variations are cyclic, with interval, f_i, determined by the difference distance between the path from the transmitter to the direction-finder via the reradiator and the direct path. In the present experiment this distance is x, so that

$$f_i \simeq \frac{300}{x} \text{Mc/s} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

For a structure which resonates over a wide frequency band, a close estimate of $\Phi_{max}x$ may usually be obtained with one frequency run; but for narrow-band resonators, or when x is small, a frequency run at each of several distances may be required to obtain a maximum error reading coincident with resonance in the reradiator.

The bearing errors produced by a large water tower are plotted in Fig. 4. In general, the cyclic interval is close to the expected value, the departures from a simple sinusoidal variation probably being largely due to phase changes of current in the reradiator as the frequency passes through various resonances. At the higher frequencies well above primary resonance, where the tower may be considered a scatter source, the error may be estimated using one of the expressions for scattering coefficient developed by Horner.[9] Although the reradiation from a rectangular sheet is predicted to rise with frequency, the experimental

Table 1

RERADIATION FROM VERTICAL RERADIATORS NEAR PRIMARY RESONANCE

Reradiator	Distance x	γ	Φ_{max}	$\Phi_{max}x$	
				Experimental	$1{\cdot}04\gamma l f(\theta)_{max}\left(\frac{180}{\pi}\right)$
	m		deg	deg-m	deg-m
Insulated vertical wire, length 22 m, lower end 5 m above ground	91	0·8	2·5	227	262
Adcock aerial, height 20 ft, spacing 12 ft, all masts earthed to 200 ft diameter earth mat	83	0·8	2·0	166	146
	114	0·8	1·3	148	
Adcock aerial, one mast connected to earth mat, others open-circuited	114	0·8	1·3	148	146
Water tower, height 120 ft, base 30 ft square, earthed through water system	170	1·0	5·5	935	1 090

bearing errors fall off above 15 Mc/s, possibly because of the open structure of the tower. Near 15 Mc/s the observed maximum error is reasonably close to the calculated value for a rectangular sheet of 2·6°.

Table 1 presents the results of measurements near primary resonance of the effects of several vertical metallic objects, compared with values calculated from the simple theory.

In the case of a mixed path, such as is encountered with the Adcock aerial on a large earth mat, the value for γ may be estimated using curves given by Wait.[10]

(3) CONCLUSIONS

The simplified expression for the maximum error due to reradiation from a resonant conductor near a direction-finder is shown to be within about 15% of the measured values. This expression is therefore quite adequate for the evaluation of direction-finding site errors where such obstacles are concerned.

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(5) APPENDIX: THE DERIVATION OF f(θ)

The current in a single loop due to the incident or undisturbed field is proportional to $\sin\phi\cos\omega t$, where ϕ is the angle between the normal to the plane of the loop and the direction of arrival of the undisturbed field. Similarly, the current in the loop due to a reradiated field is proportional to $R\sin(\phi-\theta)\cos(\omega t+\beta)$. The net current* in the loop is a minimum when

$$\phi = \arctan\frac{R\cos\beta\sin\theta}{1+R\cos\beta\cos\theta} \quad . \quad . \quad . \quad (7)$$

For small values of R,

$$\phi \simeq R\cos\beta\sin\theta \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Therefore, for a single-loop aerial we have

$$f(\theta) = \sin\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

which is simply the expression for the polar pattern of the aerial. The same expression holds for a narrow-aperture Adcock aerial, since it has the same horizontal response pattern.

For a spaced-loop aerial, where d is the spacing, the current at the output when the two loops are connected in opposition is minimum when

$$\phi = \frac{R\lambda}{\pi d}\cos\beta\cos\theta\sin\left(\frac{\pi d}{\lambda}\sin\theta\right) \quad . \quad . \quad . \quad (10)$$

when R is small. In this case,

$$f(\theta) = \frac{\lambda}{\pi d}\cos\theta\sin\left(\frac{\pi d}{\lambda}\sin\theta\right) \quad . \quad . \quad . \quad (11)$$

* A similar expression was developed by Crampton, Whipple and Mugridge.[5]

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A VERY PRECISE SHORT-PERIOD COMPARATOR FOR 100 KC/S FREQUENCY STANDARDS

By A. M. THOMPSON, B.Sc., and R. W. ARCHER.

(*The paper was first received* 30*th May, and in revised form* 16*th September*, 1958.)

SUMMARY

An instrument is described for the very precise comparison of 00 kc/s frequency standards. A sensitive phase-comparator is com-ned with a trigger circuit to produce a timing pulse at the instant the o 100 kc/s signals are in phase opposition. The time interval between ccessive pulses is determined by a counter-type chronometer. For a sec beat period a timing accuracy of 1 microsec is obtained. This rresponds to an accuracy of frequency comparison of 1 in 10^{13}.

(1) INTRODUCTION

The development of stable oscillators for frequency standards emands the very precise comparison of frequencies, and much ldditional information can be obtained if the measurements can e made quickly. The variations of frequency caused by changes f temperature, of supply voltages and circuit components, and ie effects of mechanical shock and electrical interference can ien be determined. High-stability crystal oscillators have been eveloped to the extent that short-period fluctuations in fre-uency are less than 1 in 10^{10}, so that a discrimination of the rder of 1 in 10^{11} is desirable if these residual fluctuations are to e investigated.

The most satisfactory instruments designed for short-period equency comparisons have been based on the principle of ming the duration of a single beat. To measure the beat eriod, it is necessary to determine the mes at which the two signals have a articular phase relation. In the instru-ent described by Meacham,[1] with which comparison accuracy of 1 in 10^{10} is otained, phase opposition is determined om the magnitude of the sum of the o signals, which must be very nearly ual in amplitude. In the instrument scribed by Law,[2] which has an accuracy 1 in 10^{11}, phase quadrature is defined a phase-discriminating circuit.

The instrument to be described combines atures of both the above instruments. ase opposition is determined by the use a phase-discriminating circuit to define hen the sum of the two signals, which are ljusted to be nearly equal, is in phase th one of them. An accuracy of comparison of the order of in 10^{13} has been obtained.

In each of the above instruments, a trigger circuit is used to oduce a timing pulse at the instant the phase comparator has e desired output, and the time between two such pulses is easured with a suitable chronometer. The measurements are ost convenient if the period is of the order of 10 sec. This rresponds to a frequency difference of 1 in 10^6 for 100 kc/s oscillators, and the above statements of accuracy are based on a difference of this order.

(2) PRINCIPLE OF OPERATION

The main components of the instrument are indicated in Fig. 1. The two signals to be compared are applied separately to the instrument, and the input attenuators are adjusted to obtain a prescribed level on the voltmeter. They are then applied together to an adding network, and the sum is amplified by a linear tuned amplifier. After further amplification by a limiting amplifier, which is designed to limit the output for most of the beat period but behaves as a linear amplifier when the sum is small, the sum is applied to a phase detector. One of the inputs is amplified in a separate channel and shifted in phase by 90° to provide a reference voltage for the phase detector, which has zero output for phase quadrature between its input and the reference voltage. With a 90° phase difference between the two amplifying channels, this corresponds to the condition that the two input signals shall be exactly opposite in phase.

The effect of adding the two signals is shown in Fig. 2. The signal from input A is represented by the vector OA, and the vector OB, representing the signal from input B, rotates relative to OA at the beat frequency. The sum of the two inputs, OC, is of varying amplitude and phase, the point C rotating uniformly

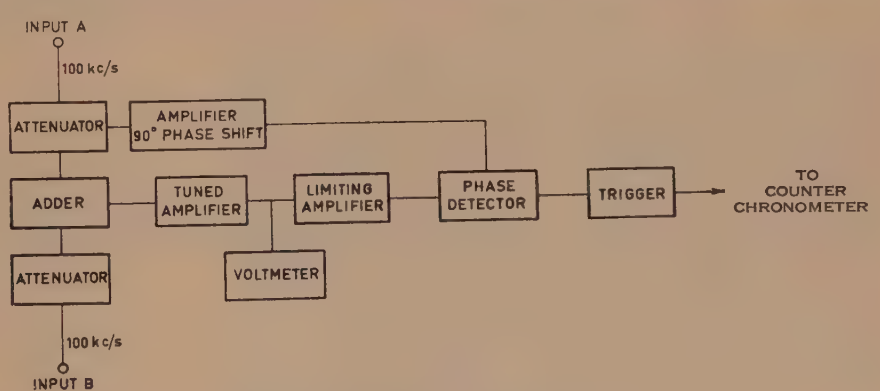


Fig. 1.—Block schematic of the comparator.

in a circle about A once per beat period. The minimum amplitude of OC depends on how nearly the two amplitudes have been adjusted to be equal. We are interested in the region where OC is small and the limiting amplifier is operating in a linear fashion.

The operation of the phase detector is represented by the second vector diagram (Fig. 3). This consists of an enlargement of the portion of Fig. 2 about O, together with POQ, which represents the centre-tapped reference voltage obtained from input A by amplification and a phase shift of 90°. In the phase detector, OC is added to OP and OQ and the two sums are rectified. The outputs of the two rectifiers are thus proportional

Written contributions on papers published without being read at meetings are ited for consideration with a view to publication.
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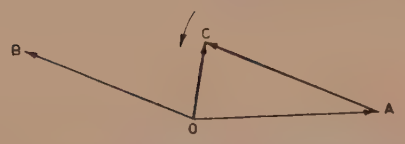


Fig. 2.—Vector diagram of adding network.

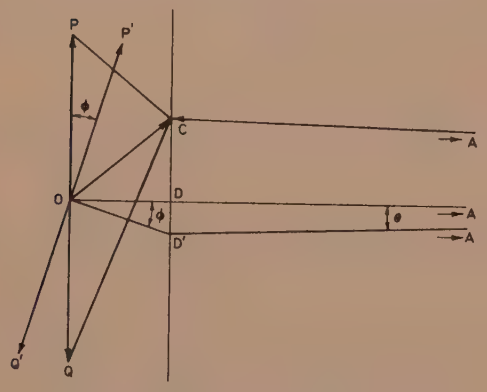


Fig. 3.—Vector diagram of phase detector.

to QC and PC, and the output of the phase detector is proportional to the difference between their magnitudes. Since OP and OQ are equal in magnitude, this difference will pass through zero as C passes through D, where OD is perpendicular to PQ. In the ideal case when OP is shifted in phase exactly 90° from OA, this is the condition of phase opposition of the input signals. If the trigger is set to trip exactly at zero voltage, a timing pulse coincident with the instant of phase opposition will result. An exact measure of the time interval between two such pulses gives the beat period, and hence the mean frequency difference over the interval.

(3) LIMITATIONS

There are a number of instabilities which cause a departure from the ideal conditions and so limit the accuracy of the system. One limitation is the finite resolution of the counter-type chronometer, which amounts to ± 1 period of the counting frequency. A counting frequency of 1 Mc/s is derived from one of the inputs by multiplication, so that this limitation is ± 1 microsec. This corresponds to 1 in 10^7 of a beat period of 10 sec, or 1 in 10^{13} in the ratio of the two frequencies. To obtain this accuracy, the phase comparator must have a stability of $3{\cdot}6 \times 10^{-5}$ deg and the timing circuits a stability of 1 microsec for 10 sec, since it is the change that takes place between one timing pulse and the next which produces an error.

An unbalanced phase-change in the input attenuators will appear directly as an error of phase comparison. Phase variations in the amplifiers cause a departure from the ideal 90° phase difference at the phase detector, and the error this produces may be evaluated by reference to Fig. 3.

If the departure is the angle ϕ, so that POQ moves to P′OQ′, zero output occurs as C passes through D′. The angle $DAD' = \theta$ is the resultant error in phase comparison. For small angles, $\theta/\phi \simeq OD/DA$.

If the fractional unbalance of the inputs is α, i.e. $OA/OB = 1 + \alpha$, then $OD/DA = \alpha$ and $\theta = \alpha\phi$. Since α is of the order of 0·1%, only a small fraction of the phase variations of the amplifiers appears as an error of phase comparison.

A variation in the balance of the phase detector, or in the level at which the trigger fires, will cause an error of phase comparison. In normal operation the output of the phase comparator is 35 volts/deg, so that a 1 mV variation in either of th above will cause an error of 3×10^{-5} deg.

There is also a considerable delay associated with the low-pas filter, and any variations in this delay will cause timing errors.

(4) DESCRIPTION OF INSTRUMENT

The main features of the design are indicated in the followin descriptions of the components of the system. The operatio of most of the circuits will be evident from the simplified circui diagrams.

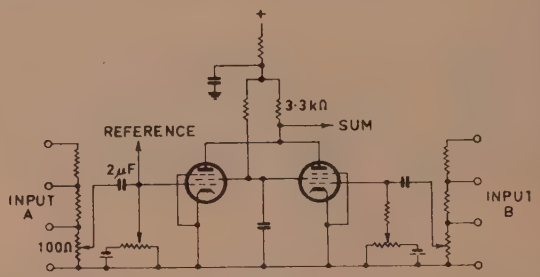


Fig. 4.—Adding network.

(4.1) Adding Network (Fig. 4)

The nominal input to the adder was fixed at 30 mV so tha a simple cathode-follower and low-impedance line could be use to couple the instrument directly into the oscillator circui preceding the usual tuned buffer amplifier. To provide isolatio between such inputs, the signals were added through pentod amplifiers into a common anode-load resistor. Extensiv screening was used to obtain minimum anode-to-grid capacitanc and with a grid-circuit resistance of 100 ohms and a gain of in each amplifier, 100 dB isolation was obtained. The outpu from each adding amplifier may be set by adjustment of th input attenuators, and fine control is obtained by variation o the grid bias of the amplifiers.

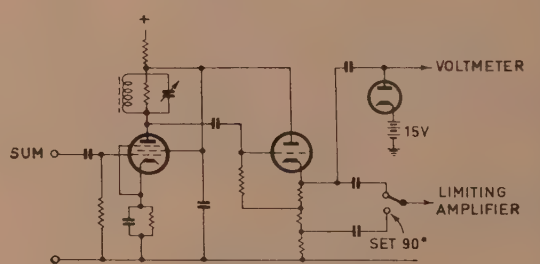


Fig. 5.—Tuned amplifier.

(4.2) Tuned Amplifier (Fig. 5)

This amplifier has a gain of 100 and a selectivity ($Q = 1$ which is sufficient to ensure satisfactory operation with osci lators whose harmonic content is the order of 1%. The tunin capacitor is used for fine control of the 90° phase shift betwee amplifying channels. The attenuator necessary for this adjus ment should be free from phase errors.

(4.3) Limiting Amplifier (Fig. 6)

This has a gain of 100 and a phase shift at 100 kc/s of 8 The limiting is symmetrical, and the amplifier recovers quick from the limiting condition.

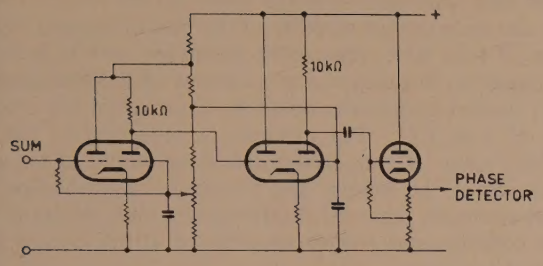


Fig. 6.—Limiting amplifier.

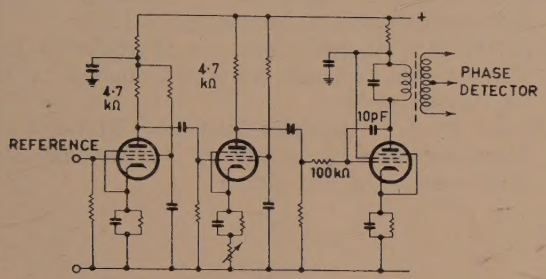


Fig. 7.—Reference-voltage amplifier.

(4.4) Reference Voltage Amplifier (Fig. 7)

The overall gain is 1 000, and the phase shift of 90° is obtained y feedback round the tuned output stage. Care must be taken minimize distortion in this amplifier, as harmonics may cause n unbalance of the phase detector.

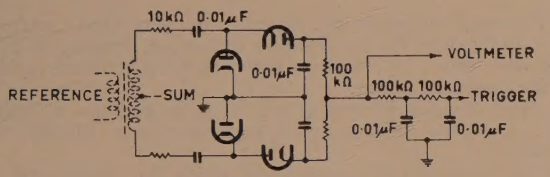


Fig. 8.—Phase detector.

(4.5) Phase Detector (Fig. 8)

This is similar to the harmonic-insensitive type described by rank.[3] The time-constants were kept as low as possible nsistent with sufficient filtering of the residual 100 kc/s present the output.

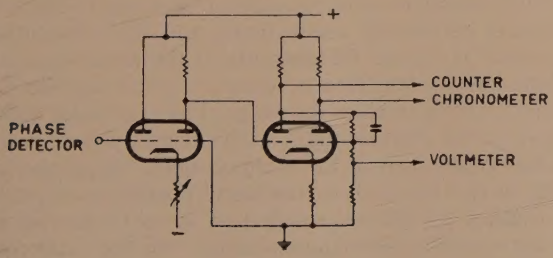


Fig. 9.—Trigger circuit.

(4.6) Trigger Circuit (Fig. 9)

It was found that the triggering level was more stable when e trigger was driven by a direct-coupled amplifier. The bias this cathode-coupled stage can be adjusted so that triggering kes place when the phase-detector output passes through zero.

(5) INITIAL ADJUSTMENTS

Before measurements are made it is necessary to make three separate adjustments to the instrument. These are:

(*a*) Adjust input stages to give equal outputs.
(*b*) Set 90° phase difference between signal and polarizing channels.
(*c*) Set trigger to trip at zero potential.

A valve voltmeter with a full-scale deflection of 300 mV is used for these adjustments.

In setting amplitudes, a biased diode is used so that full-scale deflection on the meter represents only a 1% change in signal voltage. The amplitudes may be adjusted to better than 0·1%.

In setting the 90° phase difference, the meter indicates the output of the phase detector when only the reference oscillator is connected. Additional attenuation is used to keep the signal level within the linear range of the limiting amplifier. The output is adjusted to zero by varying the phase shift of the tuned amplifier.

In setting the trigger, the meter is used to indicate the state of the trigger and the bias is adjusted to give triggering at zero output from the phase detector.

(6) PERFORMANCE

The instrument was operated from electronically-regulated power supplies and allowed to warm up for about an hour before being tested. After this period it was adjusted to the prescribed conditions. It was found that the signal balance remained within ±0·2% for some hours, and the 90° phase difference drifted at about 0·03° per hour. The maximum error from such slow changes would only amount to 2×10^{-7} deg in phase comparison over a period of 10 sec, and this is not significant in comparison with the timing error of ±1 microsec. The short-term stability of the trigger was tested using a 50 c/s standard frequency source of an amplitude to give a rate of change of 1 mV/microsec to operate the trigger. The period measurements so obtained were always within the counter limitation of ±1 microsec.

As an overall performance test, two similar instruments were used to compare the same two 100 kc/s oscillators. The two instruments were arranged to trigger at about the same time, so that the short-period instability of the oscillators would not affect the result. Measurements of beat period were made at various intervals for some three hours during which time no readjustment of either comparator was made. All but two of the 80 differences so obtained were within the limits of ±2 microsec set by the resolution of the two counter chronometers.

The above tests indicate that the limit of ±1 microsec of the counter chronometer is the major source of error. This corresponds to an accuracy of 1 in 10^{13} in frequency comparison.

(7) APPLICATIONS

The instrument is particularly useful for the development of crystal oscillators, as it is a simple matter to determine the response of a particular oscillator to various disturbances. Where the effects are small, a short-period instrument may offer the only possibility of separating them from long-term drifts. An example of this type is illustrated in Fig. 10, which gives the short-term change in frequency of an oscillator due to a 10% change in supply voltage as the phase of the maintaining amplifier is varied. The beat period is used to indicate the amplifier phase.

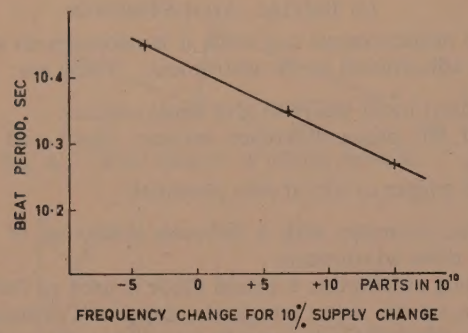


Fig. 10.—Effect of supply changes as phase of maintaining amplifier is varied.

(8) CONCLUSIONS

The technique of addition, amplification and phase detection gives a very precise definition of the beat period between two 100 kc/s frequency standards. The sensitivity of frequency comparison so obtained, of the order of 1 in 10^{13}, is much better than is necessary for the investigation of such oscillato since the short-period stability of the best of these is only of t order of 1 in 10^{10}. The extra sensitivity was included in t instrument to illustrate the possibilities of the technique, and much simpler instrument could be constructed for a sensitiv limit of 1 in 10^{11}. For example, a reduction of the limiti amplifier gain by eliminating one stage would allow a grea unbalance of the inputs, and a counter frequency of 100 k would eliminate the need for frequency multiplication. Und these conditions a trigger stability of 10 mV would give t required accuracy.

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DISCUSSION ON

'A PRECISION THERMO-ELECTRIC WATTMETER FOR POWER AND AUDIO FREQUENCIES'*

Mr. W. C. Downing (*Illinois: communicated*): The author has pointed out the problem of obtaining an exactly linear relation between measured power and output e.m.f. in a thermal convertor of the wattmeter type and has suggested the attainment of this result through the combination of thermocouple elements having different current/e.m.f. characteristics. A somewhat different approach to this same problem, used in the design of a thermal convertor manufactured by an American company, may therefore be of interest, although it has not been applied to the vacuum-type thermocouples described by the author.

The instrument has been manufactured commercially for nearly ten years for the measurement, telemetering and control of power generation and interchange in large public-utility systems. For this application certain practical considerations limit the possibilities of theoretical design. Thus, the requirement of linear response, within limits of ±0·25% of rated output, must be met for power flow in either direction, and facilities must be provided to permit a wide adjustment range of the output ratio. The former requirement prevents the deliberate introduction of corrective terms of the I^2 type, while the latter requirement indicates the use of a number of thermocouples in series, all having the same characteristic.

A basic wattmeter-convertor element of this type consists of six identical pairs of directly heated thermocouples in air. Operating the thermocouples in air means that an appreciable portion of the heat transfer is by convection and that radiation may be neglected. The major portion of the heat transfer, estimated at two-thirds of the total, is by thermal conduction along the heater and thermocouple wires.

The linearity of the power/e.m.f. relation is then determined by several factors:

(i) For most thermocouple materials the generated e.m.f. increa more rapidly than the temperature difference, tending to produce 'rising load curve'; i.e. a relation in which e.m.f. increases more rapi than the measured power.

(ii) Heat transfer by convection tends to produce a 'falling lo curve', since the heat transfer increases more rapidly than t temperature.

(iii) Heat transfer by conduction along the heater and therm couple wires may tend towards either a rising or falling load cu according to whether the temperature coefficient of thermal condu tivity of these components is negative or positive. Most alloys ha positive temperature coefficients of thermal conductivity, so, general, the effect of thermal conductivity is in the direction of a falli load curve.

The use of alloys for the heater and thermocouple elements this design resulted in a net effect in the direction of a falli load curve; i.e. factors (iii) and (ii) overcame the effect of fact (i). Pure metals, however, in general have negative temperatu coefficients of thermal conductivity, and the substitution of pure metal as one of the elements of the heater-thermocou combination was therefore indicated. Since it was felt desira to maintain constantan as the material for the heater and for o element of the thermocouple, molybdenum was introduced the other component of the thermocouple. By proper propo tioning of two materials it was found possible to adjust the heat transfer by thermal conduction so as to provide a lin load curve within the required limits. As the total correcti is small, exact proportioning is not required, and normal tol ances for dimensions have been found adequate.

In one special application, requiring higher accuracy but wide adjustment range, the method of 'mixing thermocouple as suggested by the author, was employed. In this case, substitution of Nichrome for molybdenum in two of the pairs of thermocouples resulted in a load curve within ±0·1 of rated output.

* HILL, J. J.: Paper No. 2461 M, January, 1958 (see 105 B, p. 61).

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

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